

Vehicular Dynamic Grouping: Virtualization and Network Re-orchestration

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Abstract

The dynamic and heterogeneous features of vehicular networks (VNs), coupled with rapid data flow within the topological structure of VNs, present challenges for sustaining network connectivity on the road and improving the vehicular network system architecture. This calls for an adaptive and flexible network mechanism that can keep up with the dynamics of the network in order to maintain communication between the vehicles and the transport management system and structure an intelligence-enabled network with ever-increasing traffic data demands. For instance, the dynamics of highways encourage the need for a real-time and self-organizing mechanism to handle the rapid events of vehicles entering and exiting the road. Such demands are aligned with advancements in software-defined networking (SDN) and related dynamic network re-orchestration to enable rapid response. This, in turn, promotes the concept development of software-defined vehicular wireless sensor networks (SDVWSN), where the core WSN functions are integrated into the vehicular network through softwarization. This coupled with cloud-based virtualization, which enables specific functional configuration parameters to be generated and provided to physical nodes, can be seen as a highly promising solution that can adapt to the service requirements associated with such dynamic vehicular settings. As the topological network structure requires adaptation to the road traffic and its dynamic challenges, traffic analysis modelling and full network connectivity can be provided using powerful communication techniques such as intelligent clustering (grouping) to provide a flexible network structure and connection maintenance.

The objective of this thesis is to provide a flexible vehicular grouping structure through the use of WSN core functions (i.e., 'IoT gateway', 'Router', and 'Leaf'). Virtualizing the structured group based on the programmability/softwarization of the nodes to have one or more than one function, using the Contiki-Cooja simulator, can provide the network with the flexibility to react to dynamic events through the re-orchestration with less or no network downtime. One of the other main objectives of this thesis is to identify the size of the group, which can be adaptable to the road structure and traffic scenarios, such as the road capacity of the highway, as well as the communication requirements.

This thesis has the following main contributions:

- An analytical model for the road traffic scenario (focusing on the highway case) is proposed and presented. This model reflects the capacity of the road and the possible distribution of vehicles on a road with a given number of lanes. Factors such as the road stretch, the number of lanes, the 2-second safety distance are considered in the model. This model can support the size of a vehicular group, which can be structured and re-structured on the road.
- The system architecture, which includes virtualization and network functions, is proposed to provide a flexible and controlled grouping structure prior to implementation. The proposed architecture employs softwarization that helps in testing the functions of the network to provide a working model in the virtual platform.
- The thesis proposes the self-X phases (i.e., self-formation, self-leaving, self-healing, and self-joining) for structuring and healing a vehicular group through the concept of virtualization. This approach offers a flexible and re-orchestrated group on the go.
- Utilizing the physical network for proof of concept provides the vision of a cyber-physical system. The virtual network structure where the model is structured and tested can provide the parameters and performance required to cope with the physical implementation.

The main network evaluation and performance metrics focus on testing the ideal size of the vehicular group identified based on a given road capacity. Herein, a group size of 10 vehicles with a message rate of 1 to 5 messages/second delivers 100% received messages. According to our developed analytical latency model, the hop latency obtained by Cooja is associated to the computation of the delay involved in the hop. Herein, the hop latency of 5 vehicles connected to a router node is 1 second. This is less time compared to the communication latency observed during the pre-election process. From the network re-orchestration latency point of view, research findings suggest that testing needs to focus on the 'Event Trigger' and 'Event Response' stages to reflect the time it takes for the network to go through recovery. The physical network testing and evaluation focuses on group size. Herein, the physical network experienced slightly more packets loss due to real-world factors impacting the quality of the RSSI signal, such

as the network deployment environment, obstacles, etc. However, the analysis reflects the importance of the soft trials on the virtual platform to identify the implementation test requirements of the physical network.

In a nutshell, this thesis proposes the formulation of a vehicular network dynamic grouping strategy that can adapt to dynamic events and re-orchestration demands by attaining the required response in group re-organization when the vehicular network dynamic changes occur on the road. These events pose the challenge of initiating, forming, and maintaining any structured group (such as on-going healing in response to a rupture caused by the departure or failure of network components within the group) on the road with less or no network downtime. Dealing with a structured group, such as group size, that experiences these dynamics requires analysis based on its adaptability to the road and communication requirements.

Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.

30/05/2023

Signature

Date

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List of Terms and Abbreviations

VN	Vehicular Networks
WSN	Wireless Sensor Networks
V2S	Vehicle-to-board-Sensors
V2V	Vehicle-to-Vehicle
V2I	Vehicle-to-Infrastructure
VSN	Vehicular Sensor Networks
ITS	Intelligent Transport System
IoT	Internet of Things
IoV	Internet of Vehicles
SDN	Software Defined Network
SDWSN	Software Defined Wireless Sensor Network
SDVWSN	Software Defined Vehicular Wireless Sensor Network
RSU	Road-Side Unit
DT	Digital Twin
MAC	Media Access Control
CSMA	Carrier Sense Multiple Access
TDMA	Time Division Multiple Access
Self-X	(Self-Formation, Self-Leaving, Self-Healing, Self-Joining)
RSSI	Received signal strength indicator.
LoS	Line of Sight
SeNSe	Sensor Network and Smart Environment Research Centre
RF	Radio Frequency
OS	Operating system
TI	Texas Instruments

Chapter 1 Research Motivation, Direction and Thesis

Organization

1.1 Introduction

This chapter begins with a general overview of vehicular networks (VN) and the communication strategies that take place to form the VN ideology. Adoption of the latest technologies is seen as a new imperative for flexible, intelligent operations, and a manageable VN. It then delves into the aspect of network structure and the challenges encountered by the network due to VN dynamics. As the possible VN structure based on road parameters is discussed, the clustering/grouping vehicular approach including the involved components to formulate and maintain a group is highlighted. Based on this, the challenges within the dynamic structure and the interaction with the cloud to provide the full vehicular system architecture are identified and put forth. The motivation behind driving towards formulation of VN dynamically flexible grouping approach that has the ability to adapt with dynamic events and re-orchestration demands. The mechanism of vehicular grouping with the example of using highway road for vehicles deployment is discussed. Also, the role of virtualization, Wireless sensor networks (WSN), and softwarization is stated before laying the research question. Subsequently, the aim of the research work along with the relevant objectives to be pursued towards execution of the same are stated. Then, the research output in terms of publications is listed followed by the conclusion of the chapter.

1.2 Vehicular Network: Communication Strategy and Intelligent Technologies

Advances in road and traffic monitoring applications require contemporary development of software, hardware and communication strategies between vehicles and transport management systems such as the central cloud. The embedded sensors in the vehicle or the sensors deployed at the roadside can generate associated data such as speed, location, acceleration, and communication line of sight to ensure overall road safety [1, 2]. In addition, the various types of driving style-related data can be collected, such as real-time traffic information or information about the status of vehicles in

emergency situations. Herein, the data is exchanged by vehicles through their ability to communicate with their internal and external environment via the wireless connection, thereby forming a vehicular network; consisting of vehicle-on-board sensors (V2S), vehicle-to-vehicle (V2V), and vehicle-to-infrastructure (V2I) [3, 4]. As with the increasing number of embedded sensors in vehicles and support for vehicle communication that has popularized the term Vehicular Sensor Networks (VSN) [5], vehicles have become a sensory data resource to the outside world because power is not an issue in vehicles compared to mobile devices, where the power factor is seen as a major obstacle. Also, vehicles can be effectively equipped with powerful processing capabilities that extend support for real-time applications as shown in Figure 1-1. This forms the core of an intelligent transport system (ITS), which handles communication and coordination between vehicles and their surroundings [6].

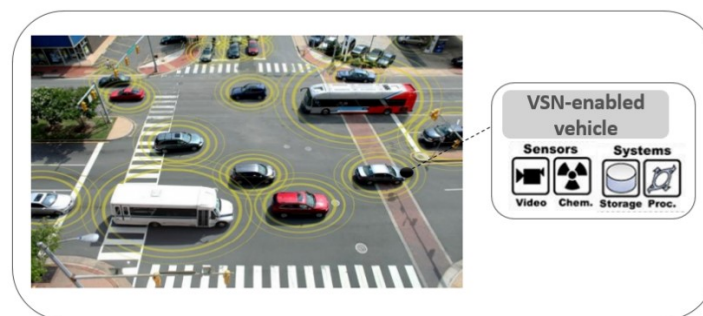


Figure 1-1 Vehicular Sensor Network [7].

In keeping with the context of VN and its role in ITS for future smart cities, adopting several technologies and paradigms can enhance the structure of VN and communication strategies for a better road system. The concept of connected vehicles and self-structured networks 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 ITS promoting autonomous vehicles on the road. This, in effect, requires highly functional sensing, communication, and computational capabilities compared to conventional systems [5, 8]. This encourages the utilization of the Internet of Things (IoT) that facilitates the connection of resources in a network. This also enables intelligent transportation of a smart city to focus on road management and safety, and vehicle communication leading

to the Internet of Vehicles (IoV) to realize real-time system monitoring [9, 10]. Furthermore, in a bid to overcome network mobility, lack of flexibility, real-time programmability, and manage the resource constraints of nodes within the topology like computational capabilities and node distribution, some advanced techniques such as intelligent clustering for VN, softwarization, virtualization, and cloud computing can be realised to offer network intelligentization [6, 11-18].

1.3 Vehicular Network Topological Structure: Approaches and Challenges

The VN environment brings with it many challenges in terms of communication, network structure and connectivity [19]. The vehicle shared space encompasses numerous large varieties of ever-changing, unpredictable service requirements [20]. In the highly dynamic topology of VN, a lane-changing scenario across the road network, as shown in Figure 1-2, can disrupt the overall network operation, resulting in network re-formation. Such dynamic events can also lead to low data transmission efficiency, unstable network environment and irregular connectivity [21, 22]. Therefore, high network mobility requires stable communication to provide related information between vehicles and expand access to the Internet on the go. This in turn enables the exchange of various types of data, such as real-time traffic data extracted from sensors onboard vehicles to facilitate passenger and vehicle services [19, 23].

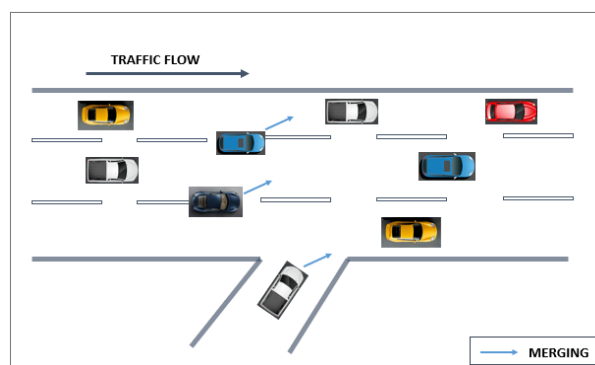


Figure 1-2 Lane changing scenario.

Vehicular network structural set-up is restricted by the road type and its regulations. Here, VN tends to adhere to a common structural formation considering the road structure layout. The road parameters, such as the number of lanes, road length, and

driving speed, can affect vehicle distribution, network density, and hence the size of the VN, which can range from small to large-scale organization [19]. Owing to the mobility of vehicles, the highly dynamic topology of VN requires spatially adjacent group management for the moving vehicles on the road. This would provide efficient and stable routes for data dissemination [24]. Therefore, VN tends to encompass a multi-layered hierarchical architecture, involving aspects such as clustering/grouping (including multiple levels of structured groups formed over the road stretch, particularly within tree-based topological orientations). Herein, utilizing such a structure to partition the network into small groups of moving vehicles, plays an imperative role in facilitating connectivity between the vehicles that are within each other's line of sight and reachable through single- or multiple-hop connectivity. The grouping approach can further support efficient communication between the vehicles and the vehicle-gateway, achieve load balancing, increase packet delivery, make the dynamic network more manageable and stable, and simplify routing in the network [24]. It is worth mentioning that as the network is bounded with structured regions, the term 'grouping' is used here to refer to a number of vehicles placed on a group based on shared sequences of communication messages and decision-making process among them.

From the group dynamic ideology point of view, the vehicular grouping approach tends to involve frequent events of constituent vehicular nodes leaving or joining any group [24]. Member nodes located in close vicinity to each other may formulate a group within the network. New members may join such a group in case they arrive within close proximity of the group while existing members may depart in the event of change of route. These events cause the challenge of initiating, forming, and maintaining any structured group in the road within low or zero network downtime. Considering these dynamic events, a group goes through the stage of exchanging information among the nodes to formulate a group or amend/update an established group. This has been looked at based on defined parameters (such as speed, RSSI (Received Signal Strength Indicator), etc.), communication strategy, and group members and owner selection (i.e., fitness model to select the best candidate). This, as a result, can construct the required topology for the network as a single-hop or tree-based multi-hop network as per the road requirements. The main challenge here is the definition of the group size that can

adapt to the dynamic changes along with the definition of the node's role/function to be part of the on-going grouping process on the road in offering the flexible structure and the rapid response to the events.

The main components involved in VN are sensing, communication, and efficient computation, IoT-based vehicular network architecture, where the cloud computing platform is employed for providing intelligent transportation services. This encompasses a multitude of software-based configuration capabilities, including virtualization, data storage, data analytics, etc., which can potentially facilitate optimal remote configuration of the nodes over the Internet, as shown in Figure 1-3. A virtualization unit within the cloud platform can offer a testing ground for running and analysing soft trials of the dynamic events occurring in the network [19, 20, 24].

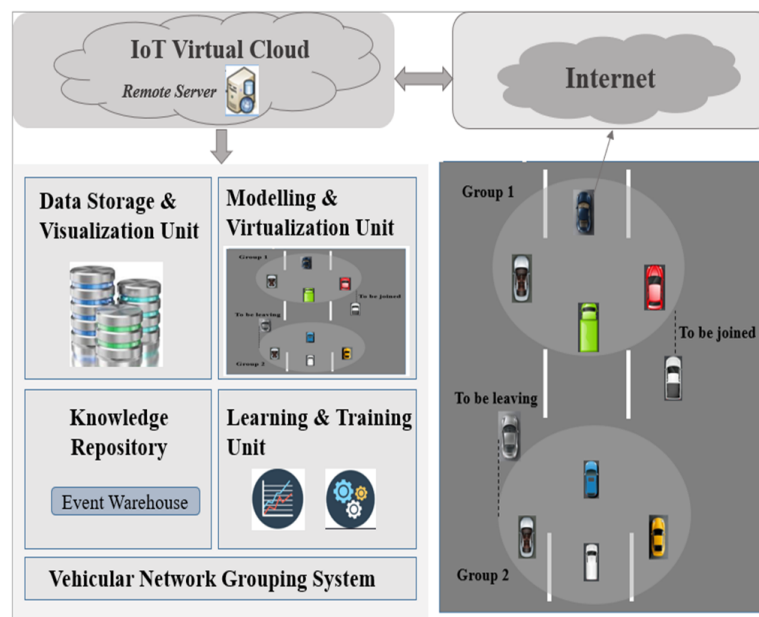


Figure 1-3 Overview of vehicular grouping system architecture [20].

The cloud-level virtualization is considered to rapidly facilitate the flexible network re-orchestration, thereby meeting some of VN's stringent service requirements, while keeping the end-to-end latency associated with the trialling process to a minimum. This can be further enhanced by using the software definition within the network to tackle the various dynamic vehicular group formation possibilities, as well as adoption of different topological frameworks for groups so formed.

1.4 Motivation for Driving Towards a VN Dynamic Flexible Grouping Approach

The dynamic nature of VN dictates its deployment approach with respect to factors such as density, topology, road parameters (road stretch, number of lanes, etc.), communication mechanism, sensing, and data acquisition requirements. The vehicular grouping technique is seen as an authentic on-road approach to ensure efficient communication within the vehicular group and the external entity (i.e., the cloud). Due to the continuous flow of vehicles, the approach could be correlated with data traffic considering a highway scenario as an example. The long stretch of highway with vehicles moving at around 100 km/h could reflect the combination of vehicles that can form a group. Considering the distance between two vehicles in the same lane (as governed by the 2-second rules), the number of hops and connectivity (i.e., RSSI) for a given group can define the extent of the group along the road. This stretch may reflect the ideal density or vehicle capacity of a vehicular group. It can also offer an indication of the maximum number of groups presented in a given section of the highway [24]. An example of the highway traffic scenario is shown in Figure 1-4 [25]. The shaded areas reflect the potential for groups to formulate in that direction of the highway.



Figure 1-4 Traffic grouping scenario on a typical highway.

As the vehicular grouping structure gives importance to the road layout, it also takes into account the rapid dynamic events that require proper response and adaptation to the occurrence of a dynamic event within the associated group of vehicles. Such events could be attributed to a number of reasons such as diverging routes to be traversed by the various nodes, switching from one group to another, members moving with dissimilar and varying speeds (owing to traffic conditions, etc.). Here, network-related formation/defragmentation events involve dynamic grouping of member nodes to enable the necessary group formations. However, a network fragmentation process arising out of events such as a node death caused by a sudden departure of a member node from its particular group would most likely result in an abrupt disruption of the sensed data flow and communication within the group. For example, in the case of the departure of the group leader, certain dependent children members nodes, (of the departing node) could possibly be disconnected from the group and thus, be rendered unmonitored. Such events are highly transitory in nature necessitating an adaptive, flexible, real-time and autonomous self-organizing mechanism [24]. Employing the recent technologies such as software defined Wireless Sensor Network (SDWSN) and integrating the core functions of WSN in VN through the softwarization approach to bring the concept of software defined vehicular wireless sensor network (SDVWSN) forward can offer a promising solution. This in conjunction with cloud-based virtualization, wherein relevant operational parameters could be manipulated to generate specific functional configuration parameters to be delivered to the physical nodes, could be conceived to be a highly prospective solution towards adaptively satisfying the service demands associated with such dynamic vehicular environments. Running trials of various such group formation possibilities can facilitate converging upon the optimal or near optimal VN topological framework (e.g., resorting to multi-hop tree-based topology from conventional star topology to increase the network coverage, and serve more nodes) in an expedited manner without interrupting the actual physical VN data collection process. The utilization of an IoT sensor network consisting of three core functions, namely 'leaf function', 'router function', 'Gateway function' can offer the required flexible re-orchestration, and hence a real-time response to an event within the network. In case of formulating a tree-based group, the layout of the network is presented by leaf nodes, router lower level, router upper level, gateway node that can

be represented by infrastructure such as roadside unit (RSU) as shown in Figure 1-5, or a mobile node.

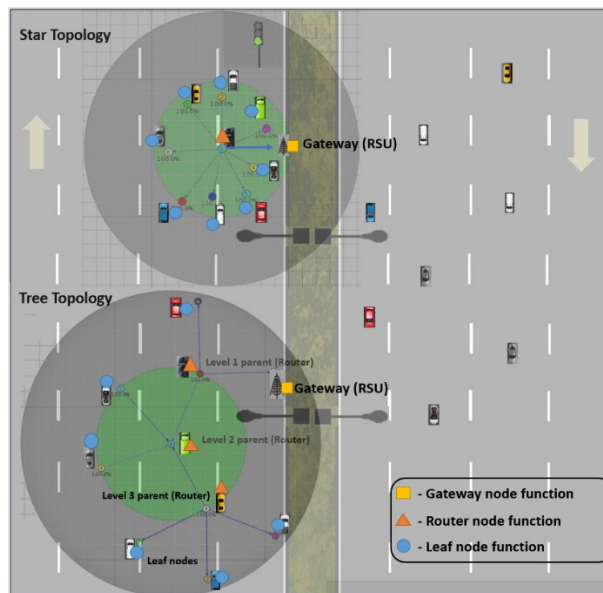


Figure 1-5 Structure of vehicular network topology.

1.5 Research Questions, Aims & Objectives

The information and background about vehicular network presented above raises the following question, which served as the impetus for this research project:

‘What would be the appropriate vehicular network organization and size that can flexibly be re-orchestrated to adapt to the road dynamics and offer timely reaction to related road events?’

The aim of this research work, therefore is ‘To develop a self-organized vehicular grouping approach for a cloud-based software defined vehicular wireless sensor network’.

The following are the research objectives towards achieving the aforementioned aim:

- To identify and model the vehicular grouping self-X phase (i.e., self-formation, self-joining, self-leaving, and self-healing).
- To utilize the core functions of WSN as software modules in modelling each vehicular grouping phase as per the requirements of each phase (such as a

scenario of having multiple functions in one node). This can enable the process of network re-orchestration under the dynamic events.

- to utilize virtualization in modelling and testing each phase and as an integrated phase.
- to identify and analyse the size of vehicular group considering the road analysis (road parameters and regulations) and testing the defined group from the network point of view.
- to analyse key performance indicators like packet loss, latency, network group size and others that relate to the concept above.
- to validate the concept using the physical network implementation, with a focus on testing key virtual network components such as group size. This, in turn, provides the organization for cyber-physical architecture that facilitates the virtual testing of the network to apply the most appropriate implementation scenario to the physical network.

1.6 Thesis Organization

Chapter **1** gives an overview of the vehicular network based WSN, its applications, and the integration of the network with the IoT platform. The background area outlined in this chapter includes the network structure such as the clustering methods and motivation for driving towards the flexible vehicular grouping and the full vision towards the vehicular grouping system architecture. The research motivation, research problem statement, research aim and objectives are also discussed.

Chapter **2** provides an insight into the related literature to the important aspects associated with this research; viz., the characteristics of the road traffic with the focus on highway scenarios, communication in vehicular network based on clustering, enabling technologies in vehicular network such as softwarization, and the related performance measures in VN have been discussed within this chapter.

Chapter **3** offers the modelling and implementation tools employed towards concept development and testing. It provides an insight into the ability of various available tools including software and hardware to investigate the concept of vehicular grouping and network re-orchestration.

Chapter 4 introduces the key road traffic parameters involved in the road traffic modelling. The development of the proposed vehicular grouping approach through the phases of self-X (i.e., self-formation, self-leaving, self-healing, and self-joining) concept is laid out. This chapter presents the ideology of the key aspects of the proposed approach and its major components, such as the functionality of the nodes in supporting the grouping phases. This is based on the wireless sensor network core functions (i.e. leaf, router, and gateway). Mainly, the chapter discusses the ability of the network to be flexibly formulated and re-orchestrated under various conditions, for example, a functional node departure from the network. The proposed system architecture is described wherein technologies like software defined network (SDN) is utilized in VN promoting the concept of SDVWSN. Then, to enhance the grouping concept on the road, the formulation of the road traffic analytical model with a focus on parameters like road capacity is presented. From the performance measure point of view, the chapter is focused on the analytical latency model for network formulation and re-orchestration.

Chapter 5 presents the network modelling and simulation of the vehicular grouping phases including the road traffic model. MATLAB and Contiki-Cooja network simulator are presented in this chapter for the road traffic analytical model and self-X phases grouping model. The concept is tested based on the road capacity, as one of the parameters, and the network performance with emphasis on the group size. This in effect requires identification of the ideal size of a given group on the road, through the road traffic analysis and network performance, as it goes through the phases of grouping. The transaction latency in formulating the network is discussed mainly with the comparison between single and multi-hop grouping structure. The latency occurred in the event of network fragmentation and network re-orchestration is one of the key performance measures that is focused on in evaluating the process.

Chapter 6 presents the cyber-physical system wherein the physical network implementation using Texas Instruments CC2538 (TI CC2538) sensor nodes is provided. The key performance indicators such as evaluating the node (such as gateway) capacity based on packet drop is discussed. A comparison between the virtual and physical scenario is highlighted.

Chapter 7 concludes the research work, along with the future work.

1.7 Research Outcomes- Publications Based on the Thesis Work

A total of four papers have been published over the course of this PhD research work as listed below:

1. Al-Hamid, D.Z. and A. Al-Anbuky., "Vehicular Grouping and Network Formation: Virtualization of Network Self-healing". in 5th International Conference on Internet of Vehicles, IOV 2018, Paris, France, November 20-22, 2018. pp. 106-121. Springer.
2. Al-Hamid, D.Z. and A. Al-Anbuky., "Vehicular Network Dynamic Grouping Scheme". in 2021 IEEE International Conference on Autonomic Computing and Self-Organizing Systems Companion (ACSOS-C), DC, USA, 27TH September-01 October 2021. IEEE.
3. Al-Hamid, D.Z. and A. Al-Anbuky., "Vehicular Grouping Protocol: Towards Cyber Physical Network Intelligence". in 2021 IEEE International Conferences on Internet of Things (iThings) and IEEE Green Computing & Communications (GreenCom) and IEEE Cyber, Physical & Social Computing (CPSCom) and IEEE Smart Data (SmartData) and IEEE Congress on Cybermatics (Cybermatics), Melbourne, Australia, December 06-08, 2021. IEEE.
4. Al-Hamid, D.Z. and A. Al-Anbuky., "Vehicular Intelligence: Towards Vehicular Network Digital-Twin". in 2022 IEEE 27th Asia-Pacific Conference on Communications (APCC), Jeju Island, Korea, October 19-21, 2022. IEEE.
5. Al-Hamid, D.Z. and A. Al-Anbuky., "Vehicular Networks Dynamic Grouping and Re-Orchestration Scenarios". *Information* **2023**, *14(1)*, 32; <https://doi.org/10.3390/info14010032>. This article belongs to the Special Issue Internet of Everything and Vehicular Networks.

1.8 Conclusion

The chapter provided an introduction to vehicular network communication strategies and the challenges associated with the dynamics of the network. Herein, the challenges in the network topology and the structural approaches were discussed. The clustering

strategy was emphasised as one of the promising approaches for vehicle networks since road dynamics have an impact on the network topology. Due to the network's high mobility, the use of technologies like softwarization to provide network adaption was proposed. These key components led to outline the motivation for opting for the vehicular grouping approach that can accommodate and manage the dynamics of the road. The mechanism of the grouping approach with taking example of highway scenario was discussed. Also, the role of the enabling technologies and wireless sensor networks in realising the grouping approach was highlighted. As a result, the 'research question', 'research aims', and 'research objectives' were outlined to carry out this research work. The chapter also provided the research output in terms of publications.

Chapter 2 Literature Review

2.1 Introduction

As with the development of vehicular network cloud-based system architecture, the dynamic and heterogeneous features of VN, coupled with rapid flow of data among the vehicles, impose significant challenges including adaptive and flexible topology, stable connectivity, decision-making within the network set-up, timely data delivery and network response time under the dynamic events [26]. The data communication management in VN has also become challenging due to limited bandwidth, line of sight, and intermittent communication among the vehicles and the cloud [27, 28]. This demands new requirements for the network topological structure that can manage the resource constraints of the nodes within the topology, such as computational capabilities, and react to the dynamic events such as road accidents. As a means to achieve this, a comprehensive and critical literature analysis of the key components involved in constructing a flexible and adaptive vehicular network structure to the road dynamics needs to be attended to. This chapter offers an account of the existing state of the art pertaining to related aspects like road traffic characteristics, vehicular clustering/grouping, network virtualization, and softwarization. Herein, specific focus is laid on the aspects of network structure based on a clustering approach, including cluster parameters, strategies and performance. The role of softwarization and virtualization in supporting the network components and flexibility is highlighted. Based on the analysis, the novelty of the proposed vehicular system architecture is highlighted including identification of the key conceptual and operational elements.

2.2 Structural Characteristics of the Road Traffic

The driving speed and the minimum distance between two consecutive vehicles have a significant impact on the road, mainly the road capacity [29]. Some of the studies have also reflected that the road is often under-congested as not all lanes are busy when demand is high [30]. This unequal lane distribution is a consequence of the lane-changing behaviour of the driver. As highways are vital part of the road network, traffic and transportation engineering studies have been conducted to analyse driving

behaviour and the effects of safe vehicle-following distance on traffic accidents [31, 32]. To maintain the safety distance in normal weather, the minimum distance corresponding to 2-second reaction time to the vehicle in front is considered [33]. Figure 2-1 shows the equivalent of the 2-second distance based on various speed limits.

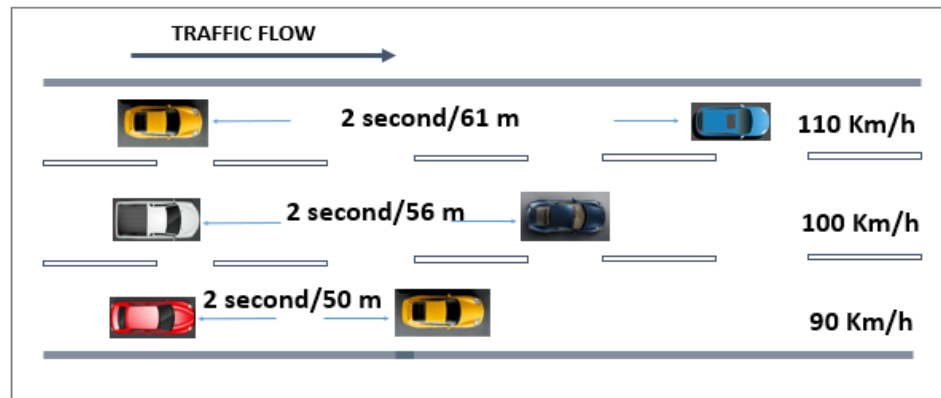


Figure 2-1 The 2-second distance on highway.

From the driving behaviour analysis point of view, the desired driving speed on the highway is considered as one of the lane change strategies [34]. Herein, drivers choose to drive within a certain speed on a stretch of highway and stick to it, even if they decide to change lanes. However, some drivers will choose a specific lane and adjust their speed to the speed of that lane. Knoop et al. [29] conducted a survey on highway driving strategies and one of their outcomes showed that the desired speed for slow drivers is <103 km/h for three-lane highways, while 103-110 km/h and >110 km/h are the desired speeds for average and fast drivers. Their survey shows that most of the participants choose a speed and adapt to the lane based on it. The authors of [29] suggest that these findings can be implemented to determine road capacity and other traffic variables such as distribution and density on the road. Hence, assumptions can be made for calculating these traffic variables based on the various speed limits, number of lanes, and road stretch [19, 35].

2.3 Vehicular Network Structure: Clustering Approach

The VN topology and its data flow in a highly dynamic environment have been studied by researchers suggesting various methods that can formulate a more robust and delay-tolerant network and improve the overall system architecture, mainly network

connectivity, stability, and scalability. These aspects have been considered as ongoing topological structural challenges impacting network performance and the data dissemination process within the vehicular system. Herein, the flow of emergency messages between vehicles is highly dependent on the dissemination process, which could be based on a single-hop or multi-hop broadcasting scheme [36]. The traditional multi-hop broadcast message dissemination scheme in a flat, dense vehicle-to-vehicle network could lead to message loss and high latency [37, 38]. To adequately comply with such demanding network structure requirements, a clustering approach can be introduced to form a reliable backbone for data dissemination. It can also be utilized as a better management mechanism to organise communication through the optimal management of vehicles with similar attributes in groups [39-43]. Therefore, the resources can be reused within the group and the operational capacity of the system can be increased [44-46]. The approach can also enhance the intelligent transportation system that encourages autonomous vehicles on the road. Some studies have been focused on the parameters and strategies of the clustering algorithm [44, 47-49]. These are discussed in the following subsections.

2.3.1 The Main Factors of Vehicular Clustering Algorithms

From a topological design point of view, a classification of cluster-based topology is demonstrated by Tan et al. [50]. The work examined the single-hop and multi-hop algorithms, with the first forming a cluster based on a direct connection from the cluster head (CH) to all members, while the multi-hop cluster facilitates intermediate members for data transmission between CH and cluster members. The authors reflect the core features of the clustering topologies considering the performance aspect. For instance, the simplicity of single-hop algorithms could impact the efficiency of the cluster, while large-scale clusters allow more potential nodes to be isolated. On the other hand, the multi-hop approach promotes intra-cluster connectivity and covers more nodes to be connected than to be isolated. This work [50] utilizes the simulation analysis for various topology-based clustering algorithms; the recent DMCS (Dynamic Mobility-based Clustering Scheme) and PMC (Passive Multi-hop Clustering) based on single-hop and multi-hop algorithms, respectively [51, 52], were the focus for showing significant improvement in performance compared to other algorithms. The cluster efficiency and

cluster numbers generated within a given area are considered to evaluate the cluster stability for the aforementioned algorithms. Maslekar et al. [53] propose a stable clustering algorithm for single hop communication where they have assumed that each vehicle knows its own location, destination and the route in advance using GPS (Global Positioning System) and digital maps. The formation of the cluster is initiated before the road intersections and is based on the travel path of the vehicle. However, the algorithm has been tested for single hop only. Some researchers have employed the hybrid architecture combining different communication protocols within the clustering structure. Herein, Ucar et al. [54] propose a multi-hop clustering based on the hybrid architecture, combining IEEE 802.11p and Long-Term Evolution (LTE), to improve data packet delivery and achieve low latency in vehicular network. The inter-cluster interference is minimized along with the overhead mitigation as a connection can be established to an existing cluster directly or via multi-hop rather than declaring itself to be the cluster head. However, different group densities (allocated number of vehicles per hop) may have a different impact on the suggested multi-hop approach.

A functional formation process of a vehicular group structure is supported by criteria and parameters for selecting the involved nodes in the group. The main role is given to the group head responsible for establishing the structural group. The cluster head selection has been of significant importance of any clustering algorithm as it improves the system performance by providing better intra-cluster and inter-cluster communication. The selection parameters that differ from one algorithm to another have been significantly presented in forming a stable and adaptive cluster structure. The parameters could be based on the number of vehicles, traffic flow of a lane, mobility model, average driving speed, average distance among collaborating nodes, RSSI (Received Signal Strength Indicator), direction and position of the vehicles [51, 55-62]. According to Hadded et al. [63], the moving vehicles in one direction could not be moving on the same end-to-end route, which could lead to the departure for some vehicles after a short period of notification time. Thus, the authors [63] emphasize the importance of the road ID (RID) where only neighbouring vehicles that move on the same road and in the same direction are considered to provide a stable cluster. In their approach, the method of electing a cluster head based on mobility features and a weight

function is the key for achieving more stable cluster. Each vehicle (v) calculates its current weight $W(v, t)$ as shown in (2-1):

$$W(v, t) = w_1 * \delta(v, t) + w_2 * |v(v, t) - \rho(v, t)| - w_3 * n(v, t). \quad (2-1)$$

The weight function model involves the parameters of average distance (δ), speed of a vehicle at instant time (v), average speed (ρ), and number of neighbouring vehicles (n). The three weighting coefficients are w_1 , w_2 , and w_3 . The vehicle that meets the requirements of the proposed model is elected as a cluster head. Then, all vehicles that are within transmission range of the cluster head become members and are not allowed to participate in another cluster head election procedure. Although the method has been presented by the weight function, it was fully depending on the map and road ID which may not be the ideal/ achievable approach for formulating the cluster.

In keeping with context of fitness function and the involved selection parameters, Malathi et al. [64] propose a super cluster head method for VANET when more nodes converge to be cluster head. A super cluster head (SCH) is a node from chosen cluster heads which will be at an optimum distance, more network lifetime, minimum delay, high packet delivery ratio, higher bandwidth, and energy. A fitness function is used to discover the SCH. The parameters are calculated based on the weight function in (2-2):

$$F_i = w_1 * D + w_2 * E + w_3 * P + w_4 * NL \quad (2-2)$$

wherein D denotes the distance, E denotes the energy of the node, P denotes the packets length and NL denotes the network lifetime.

Some researchers have pointed out the importance of mobility metrics based clustering schemes in improving cluster stability as stated by Ren et al. [65]. The authors propose a mobility and stability-based clustering algorithm wherein the mobility metrics are used for cluster formation. This approach aims at selecting the most front vehicle as a temporary cluster head wherein it assigns the node that is closest to the centre of the cluster as a cluster head. However, this could cause latency during the process of cluster formation. Furthermore, such approaches are more suitable for simple road structure as cluster members join the cluster in a one-by-one style. Taha et al. [59] consider the metrics of relative velocity, relative position, and RSSI for selecting the cluster head in

their lightweight group authentication scheme. However, factors like cluster size and cluster optimization to find the dominant parameter that affects the cluster head election could have been considered. Marzak et al. [66] propose a clustering algorithm based on the calculation of a node stability to be a cluster head considering the parameters of vehicle speed, distance, and probability values. The probability parameter is calculated based on a vehicle's energy consumption during transmission and reception of a packet, and a vehicle's speed. A node with a higher value of stability will be elected as a cluster head. The proposed algorithm has not been supported by simulation for the evaluation. Abbas et al. [58] introduce a method for clustering formation and electing a stable cluster head using intelligent cluster head (ICH). The purpose of the method is to reduce the number of uplink connections at the base station by reducing the number of cluster-heads in the network. The cluster head election is based on various parameters such as transmission range, speed, and the road length. However, analysing the election process of the cluster head based on the chosen parameters was not provided. Intelligent clustering scheme has also been presented by Mehmood et al. [67] through the Bayesian probabilistic estimation technique to enhance cluster stability and extend the lifetime of the cluster head. Herein, the knowledge of the current traffic flow as well as the factors like direction, distance, connectivity level, and speed difference are considered for electing a cluster head from the lane having the heaviest traffic flow. However, the proposed algorithm is used in urban scenarios with intersections without considering other road scenarios. Moreover, the naïve Bayesian algorithm requires real datasets making it inapplicable to other scenarios.

From the road scenario point of view, clustering algorithms could be based on vehicles moving in the same direction that can be clustered in one group [68]. Rawashdeh et al. [69] propose a clustering algorithm for vehicular network on highways where the speed difference among neighbouring vehicles travelling in the same direction is the main parameter to achieve a stable clustering structure. The authors have clustered the vehicles with high speed in one group and the vehicles with slow speed in another group. However, any vehicle could be left out of any cluster when its speed deviates too much from the speed of other vehicles in the cluster. A cluster formation scheme has been

proposed by Daknou et al. [70] for non- delay tolerant applications in a highway scenario. The slowest vehicle among the neighbouring nodes will initiate the cluster formation process. The parameters of selecting CH include speed difference and relative distance in which a CH is selected having smallest value among other candidates. In addition, an alternate or standalone CH will also be selected to replace the selected CH in case of departing its cluster.

From the clustering performance point of view, a variety of network parameters can impact a vehicular network performance; Mir et al. [71] analyse the effect of altering transmission frequency and average vehicle speed on vehicular network performance. Looking at the given transmission frequency range of 1-10 Hz, safety-related applications may require a higher transmission frequency to be adequate. From the simulation output, the end-to-end delay increases when the transmission rate and number of vehicles increase as well as the case with average speed ranging from 20-100 km/h. In keeping with this context, packet's transmission in a reliable manner or minimal delay is depending on the network service requirements. These parameters could be of importance for the vehicular ad-hoc communication phase to be evaluated in terms of reliability and latency before initiating the cluster formation phase. In keeping with the vision of clustering performance evaluation, Nasr et al. [72] propose a clustering-based VANET routing protocol (CBVRP) which is mainly based on location and velocity for cluster head election. The protocol performance is evaluated based on end-to-end delay wherein it shows less delay due to the stability of the algorithm unless a change in a cluster structure takes place. Besides, the algorithm stores and maintains the route as a backup which reflects reliable packet delivery ratio. An analytical model for evaluating the performance of a clustered vehicular network is proposed by Pal et al. [73]. This model is aiming to emphasise the metrics of throughput, messages received, and end to end delay from the mathematical point of view and to verify the simulation results obtained from any network simulator. Table 2-1 outlines the comparison among some of the clustering approaches.

Table 2-1 Clustering algorithms.

Clustering Factors	Research Work				
	Jin et al. [40]	Touil et al. [39]	Rawashdeh et al. [69]	Maslekar et al. [53]	Hadded et al. [63]
Number of Hops	1- Hop	1- Hop	1- Hop	1- Hop	1- Hop
CH Selection Parameters	Relative speed, and Distance	ID, Mobility, and Distance	Speed, Location, and Direction	Direction	Road ID
Simulation	Groovenet	OMNet++, SUMO	Own C Testbed	NCTUns	ns-2
Performance Measures	Message delivery ratio	Packet loss	Average number of clusters changed	Overhead	Packet delivery ratio

2.3.2 Vehicular Clustering Formation and Maintenance

As the cluster needs to be formulated based on the given parameters and topological requirements, the stages of exchanging the communication messages between the cooperating nodes and the execution of the suitability (fitness) model play an important role in structuring a stable and applicable cluster on the road. The significant dynamics of vehicular cluster behaviour on the road urge the need for a rapid maintenance approach to handle the major events such as departure of CH and a vehicle joining the network. As discussed above, various parameters are considered to select the optimal CH during the clustering process. The cluster structure strategies have been studied by researchers proposing various methods highlighting the use of the “Hello message” as the initial stage for establishing the formation process [74]. The stage of neighbour discovery and information exchange between the nodes within the transmission range is the first step towards cluster formation. The “Hello message” contains parameters chosen to select CH, such as node ID, speed and other information [75]. The vehicles receive the messages transmitted by neighbouring vehicles in their vicinity and store the received data in their buffer. The clustering algorithm by Rawashdeh et al. [69] focusing

on the slowest vehicle can trigger the clustering process by sending a temporary cluster ID as a message to the collaborating vehicles. Upon receiving the message, the other vehicles update their ID to the ID of the cluster originating vehicle to start calculating their suitability value along with the cluster originating vehicle to select the CH. For the strategy of a node joining a cluster, Ji et al. [76] discuss the possibility of a node joining a cluster when receiving the acknowledgment (CH_ACK) message from a CH. Herein, the node updates its status to Candidate Cluster Member (CCM) before sending the join request to CH. Upon receiving the (Join-Response) from the CH, the CCM updates its role to Cluster Member (CM). However, the node could be in the initial state if it does not receive a response message from CH. From maintaining communication within the cluster point of view, Hamedani et al. [77] propose a vehicular cluster-based two-level routing protocol to mitigate the link/connection failure problem using a greedy algorithm. The node that has a strong link towards the CH can send its data directly. Otherwise, the node relies on a neighbouring node that has a strong link towards CH to forward its data to CH. The best path between CH and the destination node is selected using a greedy approach based on distance and velocity. However, more computing resources are needed to send a request to the neighbouring nodes and receive a response to be informed about the Quality of Link (QoL) towards CH. The need of selecting a backup CH to avoid any disruption in communication and to prolong cluster connectivity when the main CH withdraws from its role has been discussed by Tambawal et al. [78]. The authors [78] introduce a secondary CH (SeCH) as a backup leader for the primary CH (PCH) to improve cluster stability when PCH fails in its role.

Some researchers have used an access point, such as the Roadside Unit (RSU) to improve network connectivity, send warning or emergency notifications in the event of an accident, or assist in improving network performance [79, 80]. Nevertheless, the cost of deploying a number of stationary RSUs along the road, particularly on a large scale, needs to be considered, as well as the area of deployment to cover a maximum number of vehicles [81]. According to Cavalcante et al. [82], the use of a minimum number of RSUs with the maximum possible coverage of the region (and thus vehicles) can be considered to assist in information dissemination and network operation. Mehar et al. [83] emphasise the importance of optimising RSU placement for delay-sensitive

vehicular network applications where communication duration and discontinuous connectivity need to be considered. However, some applications may necessitate the deployment of additional RSUs for greater coverage. Reliable communication is an important component of the vehicular clustering structure, which Hubballi et al. [84] improved by using a hybrid dynamic clustering method based on agent technology. The RSU plays a crucial role in initiating cluster formation and selecting the cluster head based on vehicle position and the vehicle neighbour list. Charoenchai et al. [85] emphasize the support role of RSUs by having connection links from RSU to CHs and each CH forming a single-hop cluster with its members. Cheng et al. [86] propose a centre-based clustering scheme in which eNodeB initiates the clustering process in highway scenarios in which each vehicle shares its mobility-related information with eNodeB.

Overall, a comprehensive research work and approaches for vehicular clustering have been considered to improve clustering efficiency and connection stability. Since the vehicular cluster is frequently affected by changes in network topology and vehicles can join or leave the cluster at any time, network lifetime plays a role in maintaining cluster dynamics. Herein, the challenges of network formation and recovery, and network adaptability to the road structure have not been fully investigated. Mainly, the impact of high road dynamics such as lane changes, departure of vehicles, etc. on network sustainability and a possible overhead for the system during network recovery requires more attention. Herein, considering latency and communication delivery messages as performance measures for forming and maintaining a cluster need to be associated to road dynamics. Furthermore, the size of the cluster that can effectively be accommodated in the road, whether highway or city, and can flexibly manage the dynamic mechanism within this certain size has not been considered in relation to road parameters such as road capacity. Hence, the current clustering algorithms lack the elements of cluster flexibility under dynamic changes and scalability while adhering to traffic regulations. Furthermore, utilizing technologies such as softwarization to improve the clustering approach is another significant area to be taken into consideration. This can be done by defining the functions of the nodes via software components in the virtual platform to enable a certain role for the node, such as the router and/or gateway roles.

2.4 Enabling Technologies Involved in Vehicular Network

The advancement of the Internet of Things (IoT) enables the intelligent transportation of a smart city to focus on traffic management and safety as well as vehicular communication [9, 10]. The IoT-based vehicular network may lack flexible network operation to a certain extent, as dynamic events in the network are highly transitory requiring a real-time adaptive process. Herein, the flexible re-orchestration of such demanding dynamic networks plays an important role in monitoring the operation of the dynamic physical environment. To a considerable extent, a cloud-based architecture tends to act as a viable solution in this regard since it encompasses a multitude of software-based computational capabilities, including virtualization, data and knowledge repository, and more involved operational and analytical tools [87, 88]. The key components of cloud architecture are virtualization and softwarization, which contribute to network flexibility and can tackle the issues related to the response to dynamic events [6].

2.4.1 Virtualization

Owing to the high cost and risk of damage associated with real hardware testing, virtualization has long been a widely accepted solution to perform software-based simulation testing and obtain adaptations for application to real networks. Efficient use of underlying physical functions is mainly achieved by abstracting them into logical or virtual functions [89]. Software-driven virtualization offers a testing ground for conducting and analysing soft-trials of dynamic network scenarios. Such parallel co-simulation running in the cloud backend can significantly aid in leaning out the network configuration process by means of obviating the hardware requirement (during the testing process). For example, the Contiki-Cooja simulator is adopted as a virtualization platform for certain target hardware (Motes such as Texas Instruments CC2538 Evaluation Module) [90]. Acharyya et al. [90] emphasize the importance of virtualization in driving towards a flexible IoT-based sensor network organization. By accessing real physical data for the purpose of modelling and simulating virtual networks, the organization herein benefited from improved flexibility and reduced latency by deriving appropriate feedback generated by the virtualization unit. Cloud-based virtualization has been adopted to plan and test various WSN re-orchestration scenarios when a

dynamic event occurs prior to actual implementation. Network performance (i.e. packet loss, network downtime, etc.) can be analysed so that the most appropriate re-orchestration structure can be applied to the physical network [87, 91]. This can support flexible network operation and lessen the impact of network dynamics [24].

In the context of vehicular networks (VN), virtualization promises to play a key role in meeting Quality of Service (QoS) requirements and enhancing network flexibility while simultaneously reducing associated production time and related costs. The interaction between the virtualized vehicular network and the physical network on the road can lead to the Internet of Vehicles (IoV) paradigm. This has emerged as the new architecture of VN that provides reliable connectivity and presents various services through extensive sensing, storage, computation, intelligence and learning capabilities [92, 93]. Although various research studies have highlighted the importance of virtualization in the vehicular cloud for enhancing service reliability and efficiency, employing network virtualization to address the challenges of vehicular grouping high mobility and road dynamics demands more attention [94, 95].

On the other hand, considering the support of the cloud for performance analysis and the existence of a virtual entity to deploy and test the possible re-orchestration of network formation, the conceptualization of the digital twin (DT) can be used for the virtual representation of the real physical component. Researchers have looked into the concept of DT from the manufacturing process point of view, where the product information is present from the beginning of life to its disposal [96]. Importantly, the context of network twinning reflects two main aspects, namely the dynamic behavior of the network and the history of the main critical events. The use of models and data including algorithms from the DT enables the realization of new services with low effort [97, 98]. Applying this advanced technology to vehicular networks can involve significant costs and complex tools. Therefore, utilizing tools like the Contiki-Cooja simulator allows for trailing network scenarios and testing performance virtually to obtain the best network structure that can be applied to the physical network [24].

2.4.2 Softwarization

The increasing number of wireless sensor nodes requires network management in which the nodes need to be flexible in approaching the various tasks and in the processing of the data. Hence, the nodes could be re-programmable if other tasks need to be prioritised during network operation [99]. Software-defined network (SDN) has been proposed as another major trend in networking due to its potential in facilitating the network management, increasing network capability, easing virtualization within the network, and allowing for innovation through network programmability [100-102]. In a bid to enable adaptability and flexibility in WSN, the integration of SDN into WSN is referred to as software-defined wireless sensor network (SDWSN) [99, 103]. This integration can enhance the management and control of sensor networks taking into account the frequent changes of network state and network functions, whereby the sensor functionalities can be adjusted by invoking various programs [104]. Furthermore, the network is easily controlled and maintained in the event of a network failure.

As the traditional VN architecture has been facing some issues in terms of the nature of network topology, communication, and network management due to poor connectivity, less flexibility and intelligence, applying the concept of softwarization can offer flexible network management, enhance traffic efficiency and improve traffic safety. Huang et al. [105] highlight the benefits of adopting the SDN paradigm for V2X communications by stating that different entities of the VN such as RSU and vehicles can act as SDN switches to facilitate the integration of heterogeneous networks. Truong et al. [106] introduce an architecture for vehicular networks as a solution called FSDN. The scheme is a combination of two emerging paradigms, Software Defined Network (SDN) and Fog Computing. The SDN-based architecture offers flexibility, scalability and programmability, while fog computing offers services related to delay and location information that could meet the demands of future vehicular network scenarios. Truong et al. [106] point out the components and the roles of their system such as SDN controller, SDN wireless node, SDN roadside unit and cellular base station to show the potential of this network. However, there is no indication of testing of the proposed conceptual architecture.

Despite the fact that SDN has advanced with the development of intelligent vehicular network (VN) approaches, its integration with the VN dynamics, mainly grouping approach and its alignment with the road regulations requires further investigation.

2.5 Conclusion

In conclusion, this chapter outlined and provided a detailed critical review of the key components that could be of great importance in formulating a flexible vehicular grouping system. The characteristics of road traffic with a focus on highways are highlighted. The analysis mainly reflects the importance of the vehicle following distance, such as the 2-second distance reflected in the road traffic parameters. The clustering algorithms pertaining to the main factors involved in clustering and the stages of formulating and maintaining a cluster are presented. The analysis showed that in vehicular clustering algorithms, there is a glaring lack of constructing a flexible mechanism to overcome the dynamics of the clustering topology and determining the optimal cluster size that complies with the road traffic situation. The performance-related aspects of the cluster in terms of 'formation' and 're-formation' under the road dynamics have not been sufficiently focused on and worked upon. In addition, the ability of a network to be re-orchestrated whenever is needed to serve a given dynamic event has not been explored in the literature.

As a means to achieve this, the intelligent, self-organizing vehicular structure can be employed to enable rapid response, where the topology can be re-orchestrated through software definition. This can be aligned with advancement made in software-defined network (SDN) while running the various operational clustering scheme phases. Therefore, the vehicular network structure needs to be looked at from dynamic grouping through phases of self-formation, self-leaving, self-healing, and self-joining based on wireless sensor network (WSN) functions. 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 physical implementation. Hence, the cloud can support the performance analysis through the virtual unit, where the possible re-orchestration of the network behaviour can be deployed and tested prior to the real-world implementation paving the way to the cyber-physical system [19, 24]. To evaluate

the performance of a given group and its ability to be re-formed under dynamic events, the capacity of the node formulating the group of given size (based on the number of hops) needs to be aligned with the road parameters such as road capacity, node distribution, and thus road density. The performance of the scheme needs to be critically analysed in terms of latency to highlight the time required for the network to progress through the phases of self-X (i.e., Self-formation, self-leaving, self-healing, and self-joining). This should be aligned with the road analysis reflecting the life cycle of the group through life, sustainability, and death. The ability of a node with a defined capacity to perform and deliver the communication messages to the associated connections (nodes) needs to be tested [35].

The aforementioned aspects tend to form the key components towards converging upon a novel virtualised flexible vehicular grouping approach based on a software-defined vehicular wireless sensor network (SDVWSN) that is able to meet the requirements for vehicular group reconfigurability and dynamic topology. The approach benefits from the road parameters to support the network topology and makes it applicable to the road requirements.

Chapter 3 Modelling and Implementation Tools

3.1 Introduction

The approach to study vehicular network (VN) grouping based on WSN core functions was selected considering factors related to the research aim of assessing the self-X phases of vehicular grouping scheme and road layout to support the performance of VN. It is important that the tools and methods chosen are authentically consistent with the requirements of the key research components concepts. As discussed at the end of Chapter 2, this research is motivated by two main goals. First, to provide dynamic vehicular grouping solution based on the three WSN core communication functions that provide the flexibility of the network through software definition to rapidly adapt to any change. Second, to test the scheme and validate its performance in road traffic scenarios where a given vehicular group size can be validated.

In general, the approach for investigating the development of vehicular grouping network and evaluating network performance can fall into 1) Simulation, to support a scalable developed vehicular grouping and present a virtual test unit, 2) Analytical modelling and analysis of traffic flow in relation to potential grouping and 3) Experimentation using a reduced model of a locally established testbed (physical network). Modelling and simulation are a means to verify the work and measure the performance of the proposed self-X phases for the vehicular grouping and the flexible re-orchestration under the road dynamics. Analytical modelling can specifically provide insight into the techniques that have been developed for road traffic analysis and a given performance measure. Simulations provide a reasonable approach to verify a developed vehicular grouping approach with the concept of software-defined vehicular wireless sensor network (SDVWSN) and associated virtualization. This, however, deviates from offering realistic results due to imprecise representation of VN specific constraints like mobility, network size and adaptation to road dynamics. On the other hand, real-world implementation and testbed provide more accurate data to validate the concepts, but are constrained by size, cost, effort, and time factors.

An overview of the current simulation tools is presented at the beginning of this chapter; along with a brief summary of related research on general VN and WSN simulation tools, a comparison of network simulators is highlighted based on their key features. Also, some of the mobility and road traffic tools are highlighted. Then, based on the analysis of the review, the selected tools to design and evaluate the proposed model are presented. The key components of the selected network simulator are highlighted to reflect most of the activities associated with this research. Then, the compatible hardware with the chosen simulator is presented. Finally, a brief overview of additional hardware board that can be used for further modelling improvements is provided.

3.2 Simulation Tools for Vehicular Involved Research Areas

Vehicular network (VN) modelling and simulation, mainly clustering methods, related mobility, performance analysis, have mostly been performed with various simulators. Currently, most of the work deals with the analysis of vehicular network performance from the aspect of network and mobility simulators (when the chosen network simulator does not support mobility). However, networks like VN require tools that can offer the support to the dynamic features, scalability, and performance. Also, as with the emergence of new technologies such as virtualization, the simulator being utilized needs to reflect the ideology and conceptual implementation of these related VN research elements. In other words, while simulators are great tools for VN, they need to be developed to better support its evolution. The most widely used network simulators in VN and WSN include NS-3, NS-2, OMNeT++, Riverbed Modeler (formerly known as OPNET Modeler), MATLAB for any mathematical modelling and analysis, and Contiki-Cooja [107-111].

As NS-2 [108] provides a rich collection of models and allows users to generate node movement and traffic patterns, the network simulator is utilized by authors [112] for developing and testing their cluster-based data aggregation method. This method divides vehicles into autonomous clusters led by a cluster-head. Herein, data is sent to the cluster head, which aggregates and distributes it throughout the network. The data aggregation approach was developed as an NS-2 application/Agent that was connected to every node. In the work of Zhang et al. [52] that is focused on the passive multi-hop clustering algorithm for selecting the most stable node as the cluster head, NS-2 (release

2.35) network simulator was utilized for performance validation. Herein, the vehicle speed was limited to 36km/h to 126km/h, and the maximum number of hops as 3 hops. Since scalability is a major problem in VN, it is not appropriate for VN research since it uses a higher percentage of CPU and memory when hundreds of nodes are simulated in NS-2. In addition, the tool is not user friendly with poor GUI and debugging support. NS-3 [107] was introduced to provide additional features to handle the simulation complexity in VN. This, in turn, eases out the issues found in NS-2. NS-3 is a freely available and open sourced discrete-event network simulator that is used for research and development, and education purposes. The simulation environment is based on C++ and with Python scripting interface. Drago et al. [113] present a unique framework in NS-3 for modelling AI algorithms through the implementation of a new geometry-based channel model and application for V2X, as well as a new intelligent entity (named RAN-AI) for optimizing wireless networks. However, the majority of network protocols are not supported, visualization has limited support, no good network animator tool is supported for wireless scenarios, and limited SDN implementation as an OpenFlow module is only available for wired networks to enable SDN [16, 114, 115].

OMNeT++ [109] is a discrete event simulator implemented in C++ and mainly used for queuing network simulations. It includes GUI library for animation, tracing and debugging support. OMNeT++ has been utilized in the work of [116] for modelling the vehicular communication network based on cluster-based routing. The tool is combined with SUMO [117] for road traffic simulation. However, there is no indication about the mobility modules used in this work.

Some of the research work that is based on VN and WSN applications have utilized OPNET Modeler [110] as it uses the concept of modelling domains representing the network, node, and process domains. Herein, the network topology of a communication network is defined in terms of subnetworks, nodes (the specific capabilities of each node are defined by a model), communication links such as wireless (fixed or mobile) and geographical contexts. The internal architecture of the node is described in terms of functional elements and the flow of data between them, while the process models are defined in a language called Proto-C which is based on a combination of general facilities of C or C++ programming language, Kernel Procedures, which is a library of high-level

commands, and state transition diagrams (STDs): States, Events, Actions, Conditions and Transitions. On the basis of these simulation models, the users can modify or build various network models and customize the design of the topology as required [118]. Figure 3-1 shows a simplistic scenario designed in OPNET from a point-to-point network based on transmitter and receiver vehicles moving on the road.

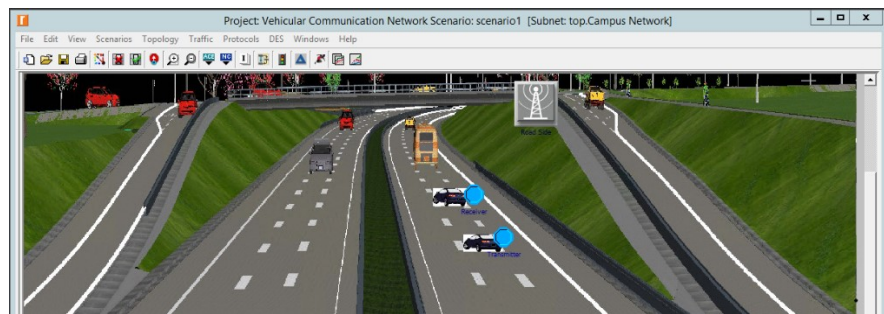


Figure 3-1 Receiver and transmitter vehicles in OPNET.

For example, a given network design requires the node within the designed topology to generate a packet containing all the related information to be processed and sent to the other nodes. This can be shown in OPNET environment as based on the node model, wherein its functionality is to generate packets, fill the field in generated packets, and send packets. The node model is structured as a generator module, processor, and radio transmitter modules, as shown in Figure 3-2.

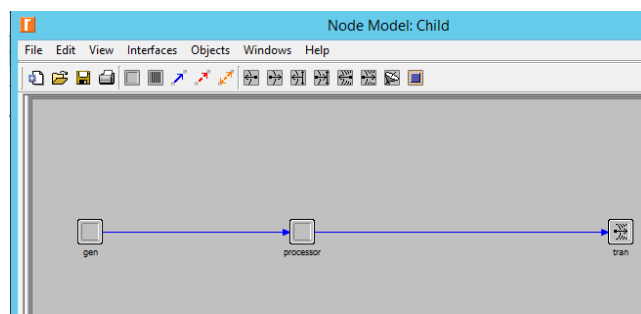


Figure 3-2 Node model in OPNET.

Each of these modules is represented by a process model to define and execute the given module within the node model. Herein, the process model reflects the internal behavior that is represented by state machines, wherein each is programmed to execute its function, e.g., the state machines within the process model of the generator module initialize the process of creating and generating the packet, as depicted in Figure 3-3.

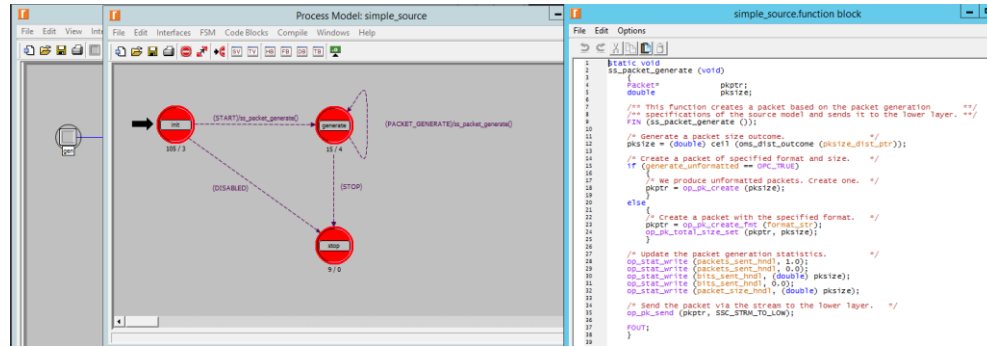


Figure 3-3 State machines within process model in OPNET.

OPNET Modeler 16.0 was utilized by Mau et al. [119] to simulate vehicular Named Data Networking (NDN) and evaluate the performance of the proposed approach based on two main scenarios. These are vehicle-to infrastructure (V2I), a hybrid of vehicle to roadside unit (V2R) and vehicle to vehicle (V2V). In V2I simulation, the LTE network involves three cells where each includes an eNodeB connected with the proposed NDN node. For the V2R and V2V simulation scenario, two RSUs are situated 200 meters apart. Ten vehicles, split into two groups, proceeded slowly in opposite directions at a speed of 5 km/h. RSUs and vehicles both have Wi-Fi cards that function within a 60-meter radio range and according to IEEE802.11g standards. The authors [119] choose OPNET in their work as it supports a realistic mobile network environment (e.g. 2.5G/3G/4G). The NDN processing modules were integrated with all network components, including mobile stations (MSs), evolved node B (eNodeB), routers, personal computers, servers, and IP clouds. Authors [118] have used OPNET to evaluate end-to-end delay, packet delivery rate, and routing overhead of their proposed Trunk Line Based Geographic Routing (TLBGR) protocol in VN. Herein, the number of vehicles is set to 100 vehicles and each vehicle trajectory is set by OPNET's define trajectory function. The range of vehicle speed is set from 30-60km/h with 1-10 packets/second as packet generation rate. OPNET is commercialized software (not open source) providing limited wireless mobility and protocols support mainly for re-configuring a given protocol.

Concepts like SDN and network virtualization require tools that can model and test the capability of a network to be tested on a virtual platform before the actual implementation, to prevent any major adjustments that need to be conducted in a physical network structure. Moreover, dealing with the virtualization platform can facilitate the dynamic planning for possible re-orchestration of the network behavior as

demanded. The Contiki-Cooja virtualization (network simulator) tool [111] has been utilized in the work of [11, 12, 90, 91] to reflect some of the mentioned ideologies. Also, with Cooja acting as a virtualization platform, virtual nodes are created by compiling and configuring the same firmware of Contiki operating system that is used to configure the actual target hardware platform of the Texas Instruments CC2538 sensor nodes. From utilizing the tool for a given application point of view, Karegar et al., [120] propose a point-by-point air- to-ground communication system considering the grouping structure for partitioning the ground network into small groups of sensor nodes distributed over large spaces through the support of an efficient communication among sensor nodes and a UAV. Herein, the UAV path flight is relaxed using the possible dynamics in WSN orchestrations as suggested in their approach. The Contiki-Cooja simulator has been utilized for establishing a communication dialogue among the UAV and ground WSN, wherein the communication scheduling method is based on the distance between the sensor nodes and the UAV that is emphasized by the RSSI measurements.

Table 3-1 shows a comparison of network simulators, listing the key features of the tools such as network scalability and mobility, and highlighting the limitations of the tools.

Table 3-1 Comparison of network simulators.

Simulators	Scalability	Mobility	Disadvantages	Language	License
NS-2	Small-Scale	Support	Very limited graphical support	C++ and Otcl/Tcl	Open-source
NS-3	Large-Scale	Support	Limited graphical support	C++/Python	Open-source
OMNeT++	Small-Scale	Support (dependant on external extensions such as Mobility Framework (MF)) [121]	Dependency on other frameworks such as INET framework for IP stack higher layers	C++/NED	Open-source (for education and reserch purposes)

Simulators	Scalability	Mobility	Disadvantages	Language	License
OPNET	Enterprise	Support	Limited wireless mobility support	Proto-C	Commercial
Contiki-Cooja	Medium-Scale	Support	Maximum nodes to be displayed are 70 nodes	C	Open-source

From the mobility and traffic modelling tools point of view, various tools including analytical ones have been used to generate the movement pattern of vehicles under a given trace. Tools like VISSIM, VanetMobisim and mainly SUMO have been used as vehicular mobility generators [117, 122, 123]. For example, Simulation of Urban Mobility (SUMO) [117] is a microscopic and multi-modal traffic simulation that can generate traces with detailed information for each individual vehicle, including their position and speed. However, the traces generated are not compatible with some network simulation tools such as NS-2, Contiki-Cooja and OPNET [124]. In addition, while it contains examples of real-world scenarios, creating complex and large-scale scenarios is time-consuming. Moreover, SUMO does not support the simulation of vehicle communication. As a result, it should be used in conjunction with other network simulators to simulate vehicular communication. MATLAB is used by [125] to predict vehicle traffic in different scenarios based on mobility parameters such as vehicle arrivals.

In summary, based on the tool analysis provided above, the selected tools for the vehicular grouping approach and road traffic analysis are Contiki-Cooja and MATLAB, respectively. The Contiki-Cooja tool offers the virtualization platform, which is one of the research elements. It also serves the softwarization concept used in this research by offering the software definition of the nodes in the vehicular group. Furthermore, it offers a testing environment for the grouping scheme prior to physical network implementation using TI CC2538 hardware. The features of the tool and hardware are covered in the following sections. For traffic analysis, MATLAB is chosen to implement

and test the traffic analysis model (discussed in Chapter 4). The mathematical and visual features of MATLAB fit well with the purpose of the traffic model as the required output to identify the road capacity, for example, is obtained.

3.3 The Contiki-based Cooja Simulation Tool

The advent of tools like Contiki, which allow the same programmes to be used for both hardware and simulation settings, has been made possible by the continual improvement in modelling and software technologies. The built-in "Cooja" tool from Contiki OS [111], which is accessible through the "Instant-Contiki 2.7 IDE" that is placed in the VMware player can be used to virtualize any IoT-based networks such as wireless sensor network and vehicular network. From the above most used simulators analysis, the Contiki-Cooja simulation tool is chosen in this research work for modelling the vehicular grouping self-X phases, as based on WSN core functions and for serving as a virtualization platform where the network operational behaviour and its node's function(s) can be re-orchestrated before the physical implementation.

3.3.1 Features of Contiki-Cooja Tool

The GUI of Cooja simulator has the layout that enables the set-up of a network with a given number of nodes. A simulation scenario can be created by adding 'Cooja Motes', as each is programmed with a given functionality such as leaf node to serve the objective of the scenario. Figure 3-4 depicts the simulation layout wherein the 'Network' window has options of viewing (by clicking on View within the Network window) the related features such as Mote ID, Radio traffic, Positions, 10m background grid, Mote type, and Radio environment (UDGM). From the transmission range point of view, any node that is clicked on will have a green circle appear around it. This is the node's specific transmission range. The selected node (node ID 1 in Figure 3-4) can communicate with any other nodes positioned within this range. The interference range of the chosen node is shown by the grey circle surrounding the green circle. If a node broadcasts packets concurrently with another node in this grey area, it cannot receive packets from that node. This is owing to interference. Nodes positioned in the white area are outside of that specific node's communication range and are therefore unaffected by any transmissions from that node. Figure 3-4 also shows the 'Simulation control' window

that offers the start button for running the simulation. It also includes the time of the simulation and the chosen speed limit for running the simulation. The other window within the simulation layout is the 'Mote output' that reflects the time and data exchanged among the nodes such as node ID, sensing measurements (e.g., vehicular speed, battery, RSSI, etc.), as shown in Figure 3-4.

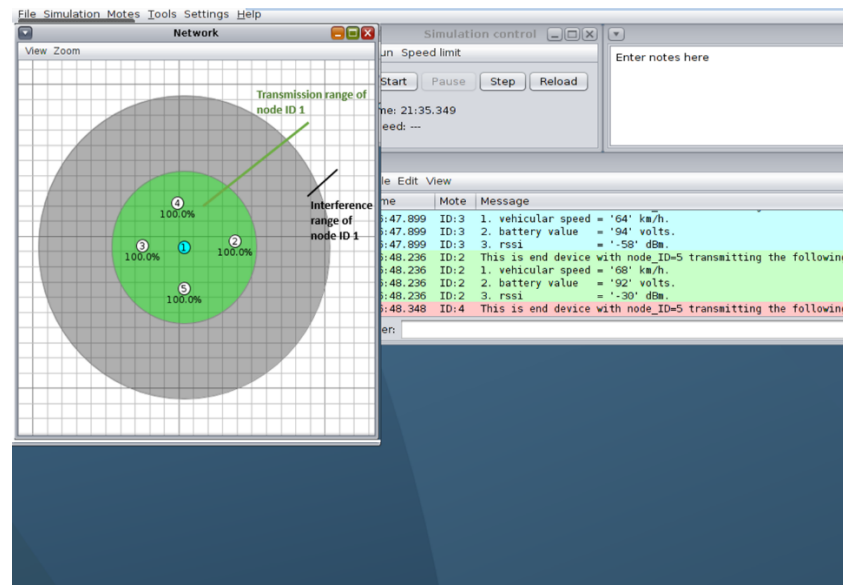


Figure 3-4 Cooja simulation layout.

Some of the other features within the Cooja tool that can support modelling and simulating a given dynamic approach is node mobility. Herein, the Cooja simulator can be used to simulate mobile networks such as VN by adding the mobility plugin to the simulator that will appear under the Tools tab as 'Mobility'. The plugin can be tested on a given node or set of nodes after creating the required motes within the 'Network' window. The positions.dat file is used by the Mobility plugin to pick a node's location (x,y) coordinates and its progressive time values. This file needs to be created under the mobility folder to instruct the nodes to move in accordance with the specified file as depicted in Figure 3-5. The (x,y) coordinates are in metres and the time values are in seconds.

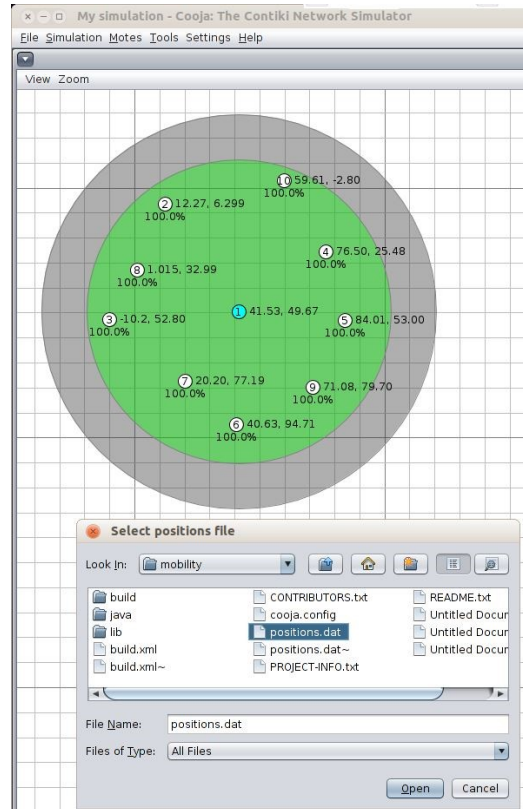


Figure 3-5 Mobility in Cooja.

From the perspective of the RSSI feature within Cooja, Cooja has an integrated RSSI or "Radio Propagation" model through which the radio signal strength of one node in relation to another node can be determined. When using Cooja, this feature, referred to as Radio, can be found under the "Mote Interface Viewer" option, which can be accessed by right-clicking on any of the created motes. The RSSI values obtained from this model depend mostly on distance and do not take into consideration the features of the real-world. Figure 3-6 a depicts a two-node Cooja scenario example where the RSSI value is obtained using the 'Radio Propagation' model. The distance between the two nodes is shown by the RSSI value of node ID 1 in this instance, which is -42 dBm. Due to the node's mobility, the RSSI value of node ID 1 with respect to node ID 2 will change when it moves away from node ID 2, resulting in a new distance between the two nodes as shown in Figure 3-6 b.

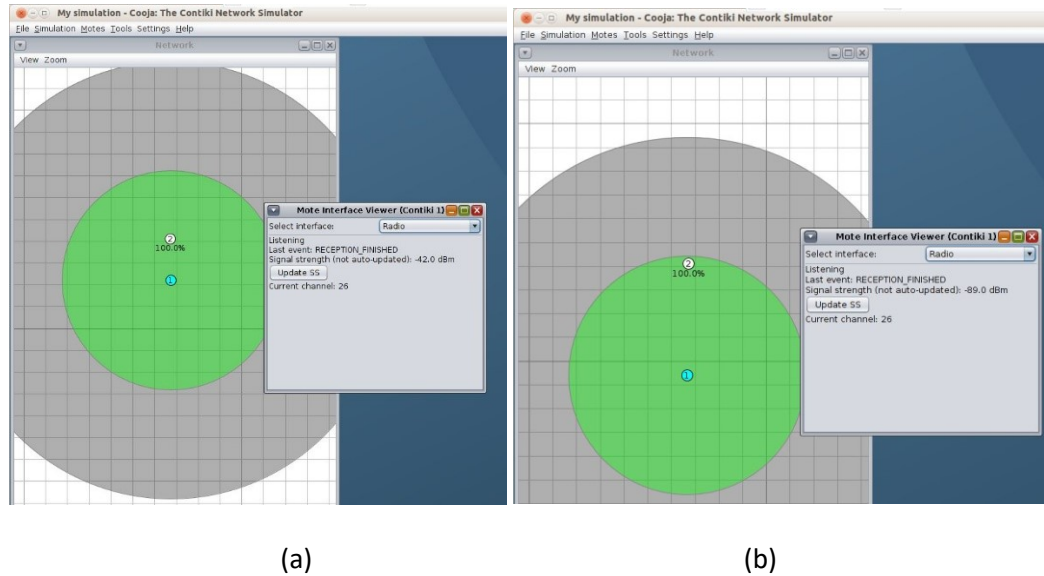


Figure 3-6 Cooja scenarios (a) two nodes within transmission range with RSSI value of -42 dBm of node ID 1; (b) two nodes within transmission range with RSSI value of -89 dBm of node ID 1.

Another important aspect offered by Cooja is the capability of the tool to evaluate the behaviour of algorithm on scaled-up networks. Herein, the scalability factor in Cooja is considered to test the proposed VN self-X phases in this research taking into consideration the road traffic analysis. Figure 3-7 depicts an example of a network with 10 end devices (configured as leaf nodes) with a router and coordinator nodes. Here, the leaf node's data is transmitted to the coordinator (i.e., gateway node) through the router node, offering the single-hop example. This can be further scaled based on a given approach and outcome. The network size in Cooja could reach up to 70 nodes.

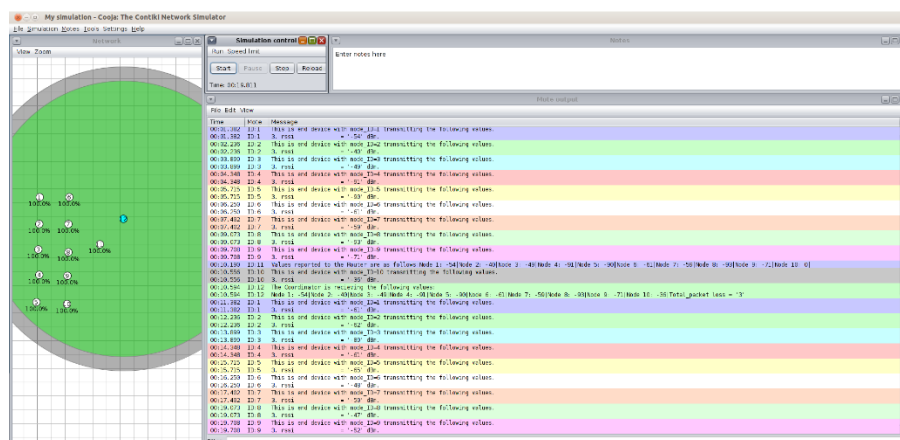


Figure 3-7 Scalable Network scenario.

For configuring a leaf node in Cooja to transmit a message at a given rate to a receiver node, the 'etimer' function in C code is used. For example, the rate of 10 samples per second is added as a value of (0.1) to the function 'etimer_set(&et, CLOCK_SECOND*0.1)'.

From the MAC (Media Access Control) layer point of view, the channel access methods such as TDMA (Time Division Multiple Access), and CSMA (Carrier Sense Multiple Access) can be accessed and switched as needed to control access to a shared communication medium. These methods can be enabled in the Contiki software C code to enable a specific channel access method. This can be applied for both of virtual motes and physical nodes (TI CC2538). Each one has a different impact on the network performance depending on the requirements of network operation. A sample of the C code for the channel access methods is provided in Section A.1 of the Appendix.

The channel access methods at the MAC layer i.e., TDMA and CSMA were utilised for testing network scenarios created and simulated in Contiki-Cooja. For sampling rate, 1 sample/second was set-up for the packet rate in the network.

- Scenario of 30 end nodes with one coordinator node

In this scenario, 30 leaf nodes (end devices) and one coordinator node were added as a network set-up to test the functionality and the polling method using TDMA. The initiation time of each node including the coordinator is different causing latency in data dissemination in the first round of the simulation. However, the coordinator received all the data, such as node ID, RSSI, from all the nodes during the overall simulation time as shown in Figure 3-8.

For the CSMA method, the coordinator node ID 31 received all the data from all the nodes in the first round, as well as during the time that the simulation has been running as is shown in Figure 3-9.

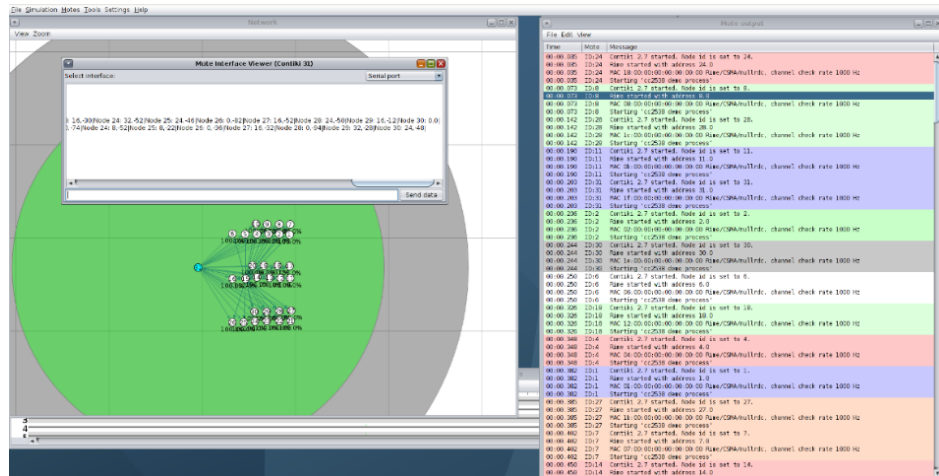


Figure 3-8 Network with one coordinator node with using TDMA.

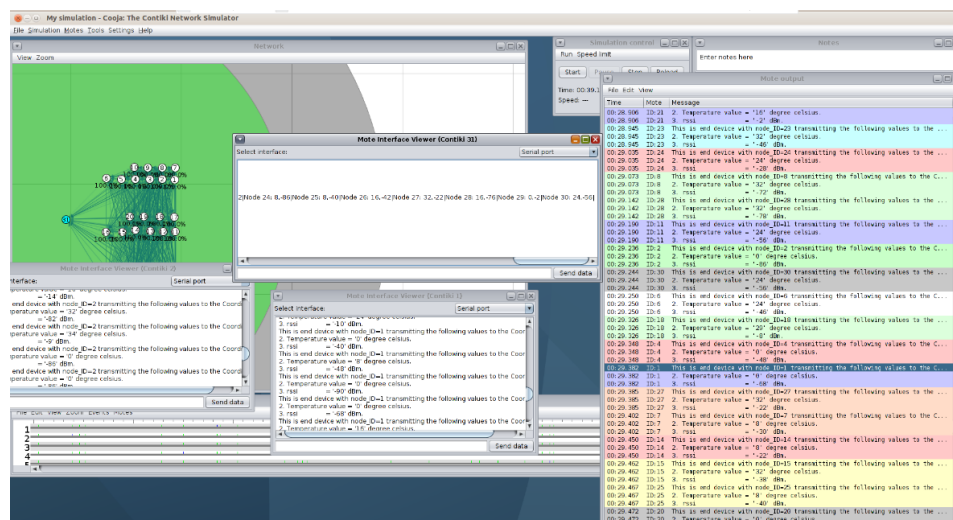


Figure 3-9 Network with one coordinator node with using CSMA.

- Scenario of 30 end nodes with three coordinator nodes

In this scenario, three coordinator nodes were placed in the simulation as depicted in Figure 3-10. Using the TDMA method for configuration, most of the data was received by the three coordinator nodes reflecting the reliability of the network when using this method. On the other hand, the latency factor is impacted by the use of TDMA as a channel access method available at the MAC layer.

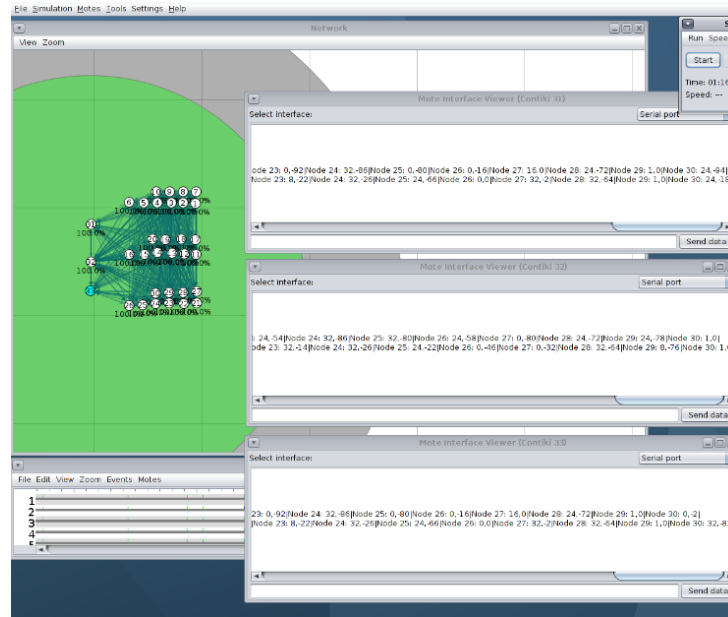


Figure 3-10 Network with three coordinator nodes using TDMA.

Figure 3-11 shows the network display with data received at each coordinator node using the CSMA method. Herein, packet loss is experienced by the network due to data collision. However, throughput and latency are enhanced through the utilization of this MAC method.

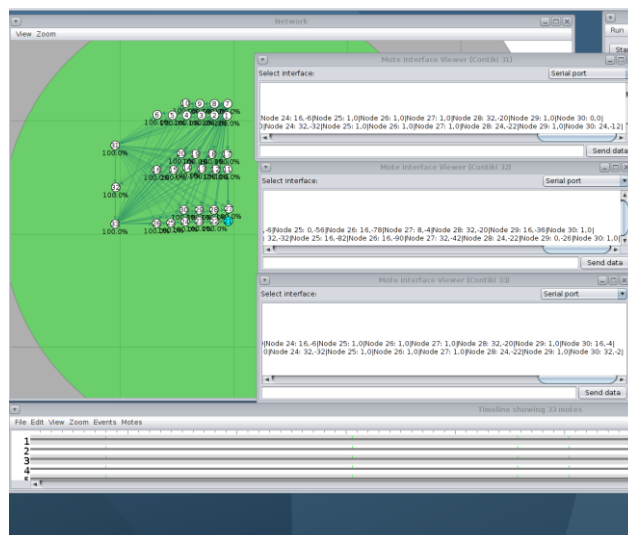


Figure 3-11 Network with three coordinator nodes using CSMA.

It is worth mentioning that the timestamps of each node disseminating messages, which appear in the Mote output, can reflect the time intervals between nodes through their ongoing communication. For identifying the packet loss encountered by the network,

'Counter_Packet_received++' can be added to the C code of the receiver node and 'Counter_Packet_sent++' can be added to the C code of the sender node (i.e., leaf node).

3.4 The Key Components for Physical Testbed

3.4.1 Texas Instruments CC2538 Sensor Nodes

The hardware representing the physical nodes within the physical network plays an important role in supporting a given ideology and offering a testing environment to the network. The Texas Instruments CC2538 (TI CC2538) wireless transceiver chips consist of the on-chip RSSI (Received Signal Strength Indicator) sensor for sensing and transmitting real-life sensed data. It is an advanced chip with IP configurability. The CC2538 EM is used in conjunction with the SmartRF 06 Evaluation board as shown in Figure 3-12 for programming purposes. These features as well as the hardware node configurability using the same program code as employed for the Cooja nodes encourage the usage of these boards for the physical network testbed implementation.



Figure 3-12 SmartRF06 Evaluation board.

These sensor nodes can be configured with either the sensing, routing, or gateway functionalities through the Contiki IDE. The C code for hardware configuration 'include' the related libraries that enable these chips to be configured, such as '#include "cpu.h"', '#include "dev/uart.h"', '#include "dev/adc-sensor.h"', '#include "dev/sys-ctrl.h"'. Each physical node needs to be configured with a unique ID through accessing the 'contiki-conf.h' header file within the Contiki, such as a coordinator node can have ID as '0xDA'. Also, a channel can be allocated to the nodes for regulating the traffic within the shared communication medium through accessing the same header file and assigning one of the available and desired channels to the nodes. The TI CC2538 node can be configured

to communicate via one of the available channels from 11 to 26. For example, assigning channel 25 as '#define CC2538_RF_CONF_CHANNEL 25'.

From the sensing measurements point of view, a scenario of turning one of the nodes into a mobile node by plugging a charger with Micro USB into the chip to provide the mobility element for conducting outdoor experiments can be used to examine the effect of RSSI on the hardware network (this will be discussed further in Chapter 6). Figure 3-13 depicts the TI CC2538 Evaluation Module (EM) with Micro USB.

The other scenario is manipulating the Radio Frequency (RF) transmission power of the TI CC2538 module to reflect the impact on the network in offering different RSSI values (this will be discussed further in Chapter 6).



Figure 3-13 TI CC2538 board with Micro USB.

3.4.2 Raspberry Pi

The widely used Raspberry Pi (RPI) is a small single-board computer that is adaptable, affordable, fully customizable, and programmable with contemporary high-definition multimedia capabilities, as shown in Figure 3-14, and is equipped with Internet connectivity [116]. It can be seamlessly integrated within the domain of WSN and VN applications for research and prototyping purposes. The RAM memory, the CPU (central processing unit), the power supply connector, the USB ports (where the Wi-Fi USB dongle or adaptor can be attached), the Ethernet ports, the GPU (graphics processing unit), and the lower-level peripherals of General-Purpose Input Output (GPIO) pins that

can be used for I2C, UART, SPI-based serial communication buses or interfaces, among other components, are all found on a RPi board. It has a slot for an SD card, allowing it to be utilised for datalogging or large-scale data storage (in cases of Internet outage). Operating systems like Raspbian, NOOBS, and others can be used to run RPi. The board can be used as IoT gateway-capable node to collect, store, and process the received data from sensor nodes in a local database within RPi called SQLite or to communicate the received data from the sensor nodes to a remote database such as MySQL depending on the application. Also, the board can be used as a mobile node by being connected to a portable battery HAT that can be placed on top of the RPi to provide 5v regulated power supply to RPi, allowing the board's mobility to meet a specific requirement, mainly for VN scenarios. It is worth mentioning that the stored real data in the remote database within the cloud can be retrieved and fed into the Contiki configuration unit using the appropriate database interface. Contiki uses the real-time data stored in the database from the most recent test of the physical network to compile and configure a given virtual Cooja mote. This can be placed in the simulation window within the simulation platform for virtual testing purposes, thus virtualizing an established physical network.



Figure 3-14 Raspberry Pi board.

3.5 Conclusion

The envisioned VN self-X phases model based on the WSN functions model involves formulating a flexible group that is dynamically managed through the software definition of the nodes in the virtual platform. This supports the group to dynamically

be re-orchestrated when a given dynamic event takes place in which a rapid event response is required before the physical network implementation. These scenarios require the support of the road traffic to reflect the potential size of a given group through analytical modelling. The performance measures that reflect an operational model need to be fully investigated to serve the requirement of the proposed approach. Therefore, this thesis uses a network simulator tool that supports virtualization, scalable networks, and mobile networks as key features to be targeted in a tool. This chapter gave an overview of commonly used and available simulation tools including NS-2, NS-3, OMNeT++, OPNET, and Contiki-Cooja. The Contiki-Cooja tool offers the virtual platform to model and test a given network prior to the physical implementation. Scalability, mobility, and other features are convenient and beneficial in designing the network model. As the Contiki firmware is used by both Cooja tool and Texas Instruments CC2538, TI CC2538 is the target hardware for physical implementation.

Chapter 4 Vehicular Dynamic Grouping Concept

4.1 Introduction

This chapter presents the development of the dynamic network grouping/clustering approach concept where a software defined vehicular network (SDVN) is utilized, employing the recent technologies such as software defined Wireless Sensor Network (SDWSN) and integrating the core functions of WSN in VN through the softwarization approach to bring the concept of software defined vehicular wireless sensor network (SDVWSN) forward.

To facilitate the data dissemination and route optimization with the ever-increasing traffic demands, the approach is governed by the road regulations where the size of a vehicular group is bounded by a given road stretch, number of lanes, and the road type. The aim of the vehicular dynamic grouping approach is to achieve equivalent response in the re-organization of the group as the dynamic changes of the vehicular network take place on the road. The dynamics of the process demands the initial formation of new groups and on-going healing as a response to any rupture happening due to the departure or fault of network components within the group. In parallel, new vehicles/nodes may join the formulated group considering the proximity of the group while a departure from the network can take place by existing vehicles due to route changing. Reaction to these dynamics (self-X phases) may cause latency in data flow and requires efficient operation with minimal latency. The objective of the approach is to offer high degree of flexibility to the nodes in approaching the various tasks, as well as processing the data through re-programmability when other tasks need to be prioritised during the network operation. Moreover, the dynamic aspects of the vehicular grouping approach are enhanced by the concept of Wireless Sensor Network (WSN) three core functions, namely the 'Leaf or sensor node function', 'Router node function', and 'IoT Gateway function'. Furthermore, the latency analysis associated with the dynamics of the vehicular grouping approach is modelled to investigate the performance of a given dynamic group running on the road. This can be aligned with road modelling wherein the size of a dynamic group can be estimated based on the available road parameters.

This chapter is organised as follows: The next section describes the importance of road parameters in designing a vehicular grouping model running on the road. Section 4.3 provides an overview of the vehicular grouping approach. The system architecture is presented in Section 4.4. Section 4.5 details the components of the network along with the description of network functional components and the computational aspect. Herein, software-defined networking (SDN) can greatly benefit the proposed scheme in terms of cluster formation based on the future prediction of the vehicle, cluster maintenance, and a more robust cluster. The components of the self-X phases algorithm of the vehicular grouping approach, namely the self-formation, self-leaving, self-healing, and self-joining are presented in Section 4.6. Then, the road traffic model and the communication network latency model are presented in Sections 4.7 and 4.8 respectively. Finally, Section 4.9 concludes the chapter.

4.2 Traffic Scenario: Introduction to the Road Parameters

The traffic on any road type, be it a highway or urban road, is characterised by a number of vehicles distributed in different lanes. The highway scenario reflects the continuous flow and sparse layout of vehicles presenting the potential for grouping, taking into account the stretch of the road. The size of a formulated vehicular group could be bounded by the road stretch and defined by various road parameters. This could be governed by, for example, the minimum two-second rule separation distance between any two following vehicles within the same lane. The rule is mainly to determine the safe and correct following distance that a driver should ideally maintain from a vehicle in front. The current two-second rule only applies in normal weather conditions and should be extended in wet weather. Importantly, the type of communication, number of hops, and sensing measurements could also define the ideal capacity or modelling density of any group within the lane. The number of lanes on the road is another traffic parameter for indicating the density of groups accommodated within the highway sector. The speed on a 100 km/h highway could be assumed to vary from 80 – 110 km/h; hence, the calculation of the size of the group based on the two-second rule could vary accordingly. It is worth mentioning here that city roads use a much lower speed limit (possibly 50 km/h) and could also be congested with several vehicles in a shorter portion of the road; hence, increased density and possible overlap among vehicular

groups could take place. This could be considered subsequently as a more advanced level of vehicular grouping. Figure 4-1 shows an example of highway scenario where vehicles are distributed over 4-lanes within a given stretch. The distance between two vehicles is denoted as 2-second distance.

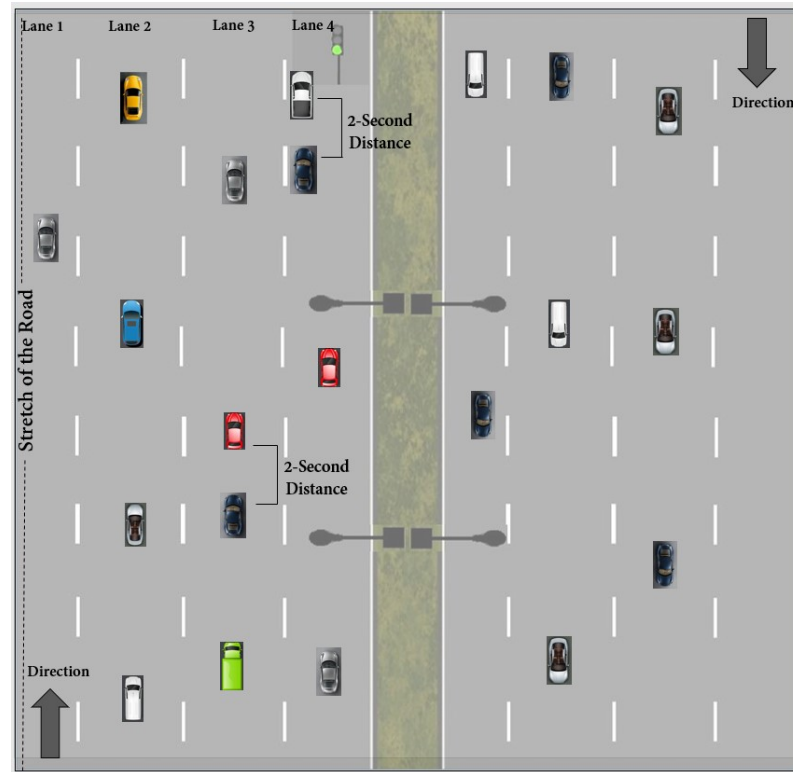


Figure 4-1 Highway Traffic scenario.

Studying the road parameters that fit our proposed vehicular grouping method, discussed in the following sections, is part of achieving a workable vehicular grouping model in a real-world scenario. Traffic modelling is discussed in Section 4.7.

4.3 Vehicular Grouping Approach

One of the issues in road management is the dynamics within the road represented by vehicles departing or joining the group through changing lanes over the road networks during the driving when a slow, stopped, or broken vehicle is spacing the road or taking the next exit towards the targeted destination. These rapidly changing dynamic events urge an immediate response, which triggers the recovery process. Offering the solution of formulated groups could assist in adequately controlling and managing information on the roads and offering drivers and passengers new services focused on safety and

collaborative driving. Hence, the network data management is one of the aspects that needs to be taken into consideration, mainly when it comes to self-adaptive networks considering the communication between the vehicles, and the gateway (be it a ground infrastructure or a mobile node). The emphasis is laid on the vehicular network topology structure to be based on the road nature, where the vehicles are distributed over multiple lanes and along the stretch of the road. Herein, the data flow in a tree network setup is seen as an authentic approach that could be aligned with the road. As the dynamic events occur rapidly on the road, dynamic re-orchestration is required to recover the network from any fragmentation that may occur in the tree-based network topology. Network virtualization and softwarization are the key components for tackling the challenges associated with the vehicular grouping approach. These are discussed in the following sections within the system architecture and network components.

4.4 Proposed System Architecture

The proposed architecture for the vehicular grouping system, where the physical vehicular network is connected over the Internet via a gateway node (e.g., stationary node like roadside unit or a mobile node like a vehicle or UAV) to the IoT virtual cloud environment reflecting the overall structure of a cyber-physical system, is illustrated in Figure 4-2. 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 to explore 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.

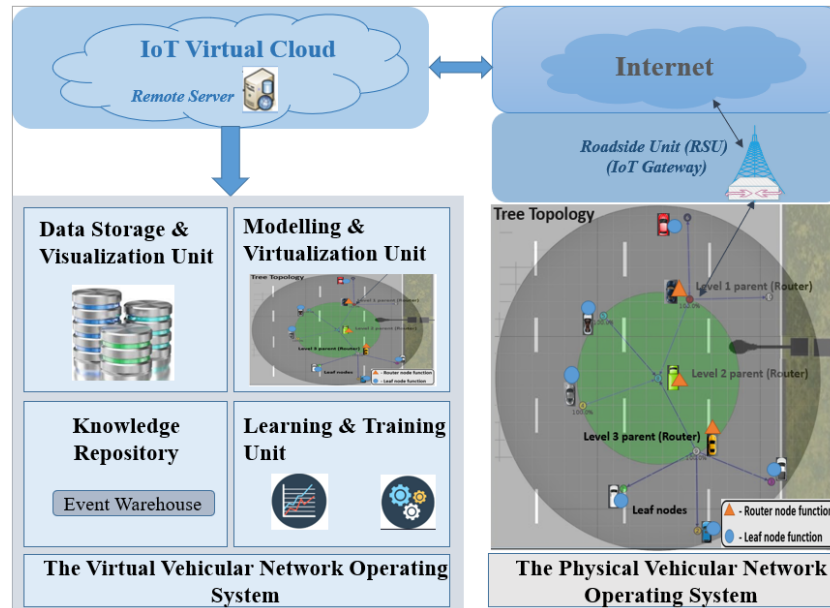


Figure 4-2 Vehicular grouping system architecture.

The functionality of vehicular nodes that is supported by the three core WSN functions (discussed in Section 4.5) can be modelled and tested on a virtual platform before its actual physical implementation. The utilisation of the virtual platform allows for the re-formulation and integration of the network and related virtual services to be deployed onto virtual nodes, as well as assessing the viability of dynamic re-orchestration of the network organisation. Herein, the virtual network provides a means to remotely monitor the logical aspect of the dynamics within the physical network by simulating the data flow that occurs there. For example, the functional role of a node can be switched through software re-formulation on the virtual platform via the implementation of any of the core functions, such as reconfiguring a leaf node to act as a router node and vice versa. Hence, the requirements for network operation and performance can be met, and any major modifications can be prevented in advance since the cloud can preserve the structure and history of the dynamics of the physical network [24]. This reflects the ability of the virtualization hosted on the cloud to considerably speed up the process of network configuration by eliminating the need for hardware to test the dynamic events and potential network recovery.

4.5 Vehicular Network Components based on WSN Functions

The increasing number of wireless sensor nodes requires network management wherein the nodes need to be flexible in approaching the various tasks as well as processing the data. Hence, the nodes could be re-programmable when other tasks need to be prioritised during the network operation. This necessitates the need for a softwarization approach in which each functional node has the capability to act and perform tasks based on the software definition [19]. The grouping approach is looked at based on the core functions of the WSN wherein the nodes within a group may assume one or more functions. The incorporation of softwarization within the WSN through the software definition of a vehicular node, where the term 'SDVWSN' is used, can help in assigning the required function for the node as part of its role within the group. A node within the group can be reconfigured to assume functions such as leaf, router, and/or gateway. A gateway capable node may also have router and/or leaf functions integrated; such a node may be dynamically configured to assume one or more of these functions and as the network re-orchestration is required. Similarly, a router capable node may also have a leaf function embedded in its software to react to the network requirements. Here it might be assigned to either or both functions as the new situation requires. For example, a router capable leaf node that has been reassigned as a router node to replace a departing router node in the network. Lastly, a leaf node can only be represented by an end device (sensor node) in the network [19, 35].

The node configured with a given function/functions is dealt with as a software component/module. This module is used to configure a given physical sensor node with enabling the related hardware libraries. In light of the degrees of freedom that each function, and thus the vehicular network system entails, it is crucial to the vehicular grouping strategy to clearly define the activities and tasks carried out by each function. The operation components/activities of each function are described below:

- **Leaf Function:** it has the key functionality of sensing and data acquisition, buffering and data computation, and communication with the upper-level node. This includes setting the sampling/data communication rate for each sensor within the firmware. The samples are buffered, and the buffer is represented by

an array defined by a size depending on the involved data. The computation activity is related to any algorithm that needs to be performed on the stored data prior to transmission to the upper-level node.

- **Router Function:** it performs the data reception from the connected leaf nodes and possibly router nodes (if the network is multi-hop structure). It can also play a cluster-head role for its group. The data sent by its connected nodes is received and accommodated in multiple arrays within the reception component. The necessary MAC layer adjustments can offer to the nodes the channel access method such as CSMA or TDMA. The sampling rate is identified for data forwarding to the higher level of the network (i.e., gateway node) to provide the required samples to the gateway.
- **Gateway Function:** the main activities include being the sink for the data gathered from the vehicular network including the sensed data from the nodes configured with leaf function and the nodes configured with router function. The transmitted data to the gateway node is received and accommodated in an array (the number of arrays depend on the number of incoming variables and number of nodes). Then, the data is transmitted over the Internet to the cloud making the gateway node act as an access point.

Figure 4-3 depicts some of the activities associated with each function discussed above that can benefit the network operation requirements.

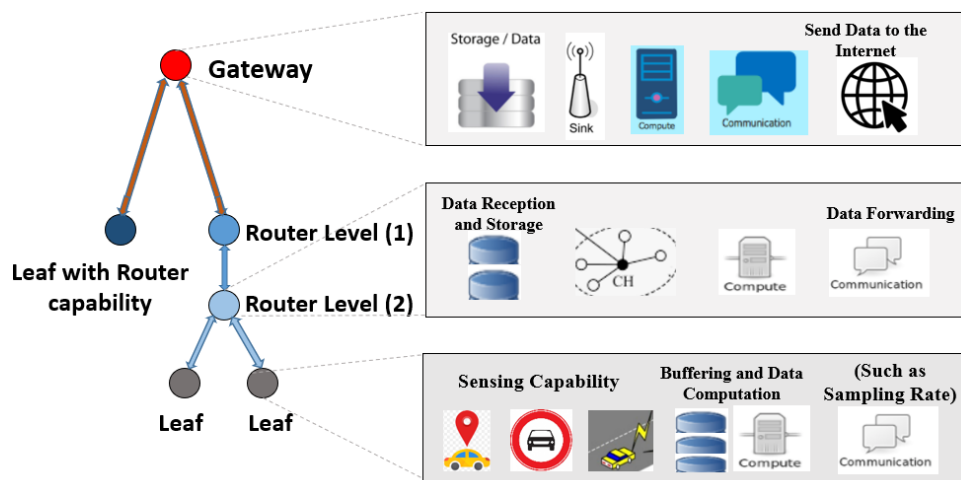


Figure 4-3 The node function activities.

4.6 The Vehicular Grouping Algorithm: Self-X Phases

From the modelling point of view, the proposed self-X vehicular grouping algorithm considering the phases of (self-formation, self-leaving, self-healing, and self-joining) is designed to be tested at the virtual level before the actual implementation. Based on the WSN functions represented by 'Leaf Sensor Node', 'Router Node', and 'IoT Gateway Node', each phase is conditionally initiated and maintained to offer the full virtual organization of a flexible vehicular network. This in effect is an on-going mechanism as some of the processes can be initiated at any time. However, the ending point of these processes is when the network becomes only a single vehicle, and the possibility of node connectivity is not available. This could relate to the vehicular node being in a highway, its transmission range with respect to other nodes, and the speed compared to the speed of other vehicular nodes. Herein, the lifecycle phases of the network dynamics can be reflected by networks running on a highway wherein each has its own lifecycle. Each network sustains its integrity with members until most of its members leave the network. Figure 4-4 a depicts the state machine of the grouping approach design reflecting the main phases. The initial process is when there is a call for network self-formation. The conditional transition to the self-healing state, for example, is the departure of a router node from the formulated network (the free-running state that is running the network after the self-formation state is completed). When the network is healed by a replacement router node, the transition back to the free-running state takes place to update the formulated network.

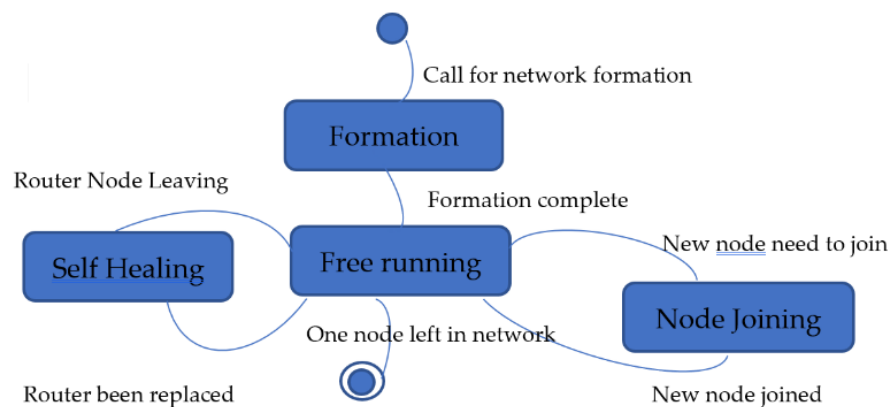


Figure 4-4 (a) State machine of vehicular grouping.

While Figure 4-4 a above reflects the high-level state machine, a detailed illustration of the internal behaviour represented by 'entry', 'do', and 'exit' of each phase, and the transitioning between states, is provided in Figure 4-4 b.

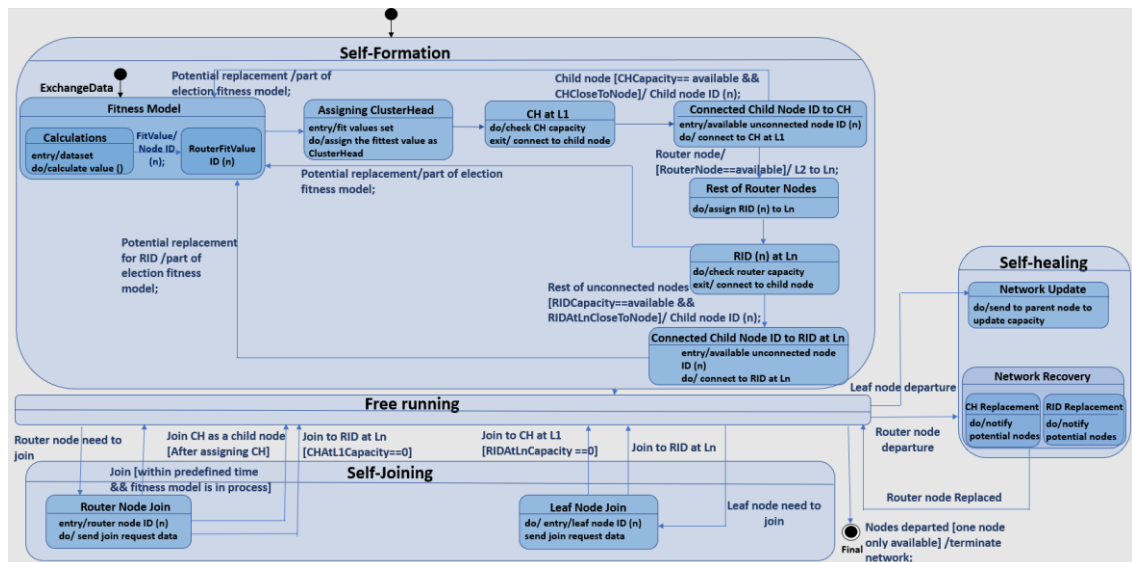


Figure 4-5 (b) Self-X grouping phases in the detailed state machine.

- **Self-Formation:** this is a compound state that has sub-states running; these are the fitness model, assigning cluster head (CH), cluster head at level 1 (L1), connected child node ID to cluster head, rest of router nodes, a router ID (RID) at level n (Ln), and connected child node ID to router ID at level n. The fitness model sub-state is initiated by exchanging data among the nodes, leading to calculations of the sub-state which has as its entry a data set to perform the required calculations. The outcome of the calculations are the fit values that can trigger the transition to the sub-state of router nodes ID with their fit values. The fitness model sub-state transits to assigning the cluster head sub-state where the entry is the set of fit values to perform, assigning the fittest value as the cluster head. Now that the cluster head has been assigned at level 1, this sub-state can check the cluster head capacity and exit this sub-state to connect to child nodes. The transition to the connected child nodes sub-state is conditional, as the cluster head capacity should be available, and the cluster head is close to the nodes. Some of the nodes connected to the cluster head are routers that need to be assigned according to the levels of the network. Therefore, the transition

from the connected child node sub-state is triggered when there is a router node as a child, and hence level 2 to level n can be taking place in the network. After the router ID at level n has been assigned, it will also check its capacity to connect to the available child nodes.

- **Self-Joining:** this process depends on the type of node that can join the network. When a leaf node requests joining, its sub-state has the leaf node ID as an entry to send the joining request to either the router node at level n where it can check the capacity within the sub-state of Router ID (RID) at Ln and then transit to connected child node sub-state if the capacity is available, or it sends the request to join the cluster head when the RID at Ln capacity is zero. Hence, the node will join the CH if it has a capacity to transition to the connected child node ID to CH sub-state. When a router node requests joining, its sub-state has the router node ID as an entry to send the joining request to the fitness model sub-state if the joining request is within a predefined time and the fitness model is in a process. This can lead to the node being part of the CH selection process where the followed sub-states can be performed as in the self-formation state. The second case is when the joining request is sent after assigning CH and hence requesting to join CH as a child node. This is a conditional transition to sub-state CH at L1 where the subsequent sub-states can be performed. The third case is when the cluster head capacity is zero and hence the transition will lead to RID at the Ln sub-state to perform the joining.
- **Self-Leaving:** this process also depends on the type of node that may leave the network. The departure of a leaf node can be from any level of the self-formulated network that will not cause disruption to the network. Therefore, the sub-state of leaf node departure needs to transit to the network update sub-state that is part of the self-healing state. The departure of a router node at any level of the self-formulated network may cause network disruption, depending on its level. Therefore, the sub-state of router node departure needs to transit to the network recovery sub-state that is part of the self-healing state.
- **Self-Healing:** this process has two main sub-states that depend on the type of departed node. When the departed leaf node is the child node of the cluster head, then the transition from the network update sub-state to the CH at the L1

sub-state within the compound self-formation state has the action of updating the capacity of CH. However, a transition to RID at the Ln sub-state within the compound self-formation state has the action of updating the RID at Ln capacity when the departed leaf node is the child of RID at Ln. When the CH departs the network, the network recovery sub-state has the cluster head replacement sub-state that can transit to the 'connected child node to the CH' sub-state within the compound self-formation state only when the potential replacement is a router child node. Then, the transition will be to the 'fitness model' sub-state to be part of selecting a replacement node. This can also involve RID at Ln to be part of replacement CH selection. When RID at Ln departs the network, the network recovery sub-state has the RID replacement sub-state that can transit to the 'connected child node to RID at Ln' sub-state within the compound self-formation state only when the potential replacement is a router child node. Then, the transition will be to the fitness model sub-state to be part of selecting a replacement node. The free running state can lead to the final state when the nodes have departed and only one node remained, causing the network to be terminated.

From the general strategy point of view, the ad-hoc communication between the nodes is a crucial stage for data collection and analysis such as reflecting the ability of nodes to assume one of the three networking roles/functions within the group. This can significantly benefit the election process when manoeuvring the orchestration of the organisation. As the network is formulated, the tree structure can have multi-hops/levels wherein each level can have a key network-connectivity component (router/gateway node) as a head node. The existing active router/gateway node could depart from its initial position and leave the group/its level due to change of route, its movement with dissimilar and varying speed, etc., causing a failure within the level or/and the whole group. Herein, the self-X mechanism is enhanced by the importance of the node function to trigger a given phase and take responsibility for any healing required in the network. For example, a node configured with a router role is a potential replacement for the departed router if the election requirements are met. The other process that emphasizes on the node function is when the unconnected leaf nodes that have not been part of any level of the network request to join an eligible router located

on any level/hop of the network. Each phase discussed in the following subsections is dealt with based on phase parameters, communication messages, and any required computation.

The key parameters for structuring the vehicular dynamic grouping phases are related to RSSI (Received Signal Strength Indicator), node capacity, and vehicular speed. Furthermore, the look-ahead approach using route information is also considered as part of the overall vision in sustaining the dynamic structure of the mobile vehicular group. Additional parameters can be utilized in some of the phases as part of the dynamic phase requirements. This will be explained further in the following subsections.

4.6.1 The Self-Formation Phase

This phase is the core process of the vehicular grouping approach as the vehicular nodes within the transmission range, when more than one vehicle is available in the neighbourhood communicating in ad-hoc fashion, attempt to formulate a tree-based network. Formulating the tree-based structure is initiated from the top to the bottom level, where the top level is represented by the head node that selects its connected nodes and forms the levels of connectivity. The vehicular network formation process flow chart and road example model is shown in Figure 4-5.

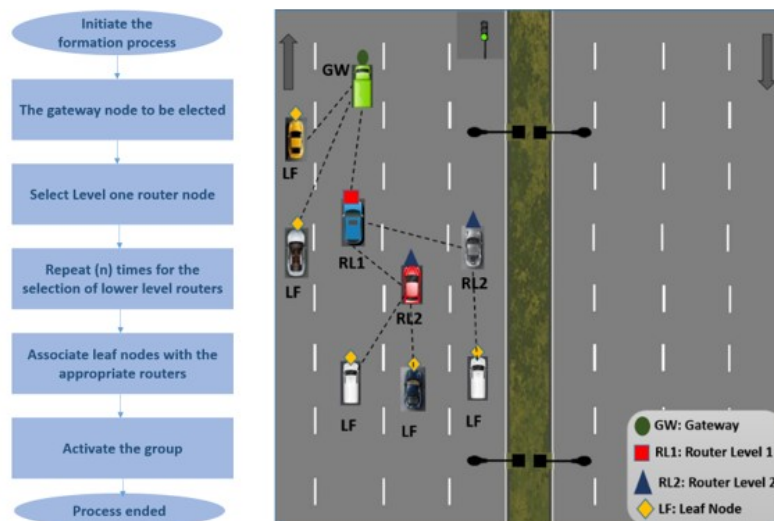


Figure 4-6 The vehicular network formation process flow chart and road example model.

The network structure process is designed through the group head fitness election model and set of communication messages to be disseminated among the nodes as listed below.

a) The Fitness Node Election Model

The suggested parameters for a vehicular node to be involved in the election competition are speed variance in relation to the group, location among the group, ability to communicate with a gateway node, and ability to act as a data router node. While the first two parameters are associated with possible measurements and could be used as fuzzy or estimated values, the other two are binary values assuming availability or not of the related features. The parameters are described as follows:

- **Distance:** the distance between two vehicles (V1 and V2) based on their coordinates (X, Y) represented by D is calculated based on the Euclidean distance. The average distance \bar{D} of a vehicle (for example V₁) with respect to other vehicles within the transmission range (this can be applied to the other vehicles that are participating in the formation process) is represented in (4-1):

$$\bar{D}_{V_1} = \frac{\sum_{i=2}^N D_{V_1-V_i}}{N-1} \quad (4-1)$$

wherein $\sum_{i=2}^N D_{V_1-V_i}$ is the sum of D_{V_1} with respect to other nodes starting with node (V₂) and ending with (V_N); N is the total number of nodes.

Due to potential obstacles, the distance may not be the best indicator of the position of the vehicles within the group when used as the single parameter in the fitness model. As a result, using a measure like RSSI could provide a reasonable indicator of whether communication is possible [19].

- **Received Signal Strength Indicator (RSSI):** this factor ensures the communication quality within the group and the gateway node. It also has an impact on the network performance wherein the weak signal message could be dropped and considered as packet loss. The accuracy of measuring the RSSI could be enhanced by considering the RSSI tolerance level of the node that could reflect the difference among the nodes of being central or close to each other. As discussed in Chapter 3, RSSI values can be collected from TI CC2538 sensor node.

- **Speed:** this reflects the vehicle movement, whether it is going to maintain its presence within the group for some time or possibly accelerate through or lag behind the group. The deviation of a vehicular speed in reference to the average speed of vehicles in the neighbourhood is significant to the sustainability of a given node within the group. The less the deviation, the more sustainable the node membership is. While the speed limit is assumed to be 100 km/h, vehicles may run at speed variable between 80 and 110 km/h. The speed average \bar{S} for the nodes is represented in (4-2):

$$\bar{S} = \frac{\sum S_n}{N} \quad (4-2)$$

wherein S_n is the speed of a node, N is the total number of neighbouring nodes. Accordingly, the speed variance S_{var} is obtained in (4-3):

$$S_{var1} = \bar{S} - S_{n1} \quad (4-3)$$

The fitness model for the election is emphasized by those variables, where each will be given weight (C) depending on its importance for the process, as well as the level of connectivity within the group. This can be formed to select a fit cluster head FCH based on the selected parameters as described in (4-4):

$$FCH = C1 * \bar{D} + C2 * \overline{RSSI} + C3 * S_{var} \quad (4-4)$$

However, in order for the formulated fitness equation to be generic for the grouping phases, the weighting factors can be normalized (i.e., each of the identified variables is assigned the same importance, say on a scale of (0-100)). This is where the fiddle factor can be introduced.

b) Communication Messages for Establishing the Tree-based Network

The communication among the vehicular nodes within the transmission range is based on a set of messages that needs to be disseminated to get the vehicular-tree network formed. This is organised based on two processes represented by the group head process and the multiple levels of connectivity process. Each node disseminates its message according to the suggested parameters which are used for running the fitness model to elect the group head and the other levels of connectivity. The description of

each action undertaken by the nodes to disseminate the related messages is provided as follows:

- **Group head selection process:** this process is firstly initiated by any of the gateway-capable nodes on the road initiating a call for forming a group. Herein, the relation between the distribution of nodes and the number of gateway-capable nodes is considered as an important factor for examining the ‘fittest node’. Once the node is elected as group head, testing its capacity can offer an indication of the best size of a formulated group, and in covering the available nodes (the testing and evaluation is discussed in Chapter 5). The communication messages are numbered in the following:
 1. In response to the initiating message, each node within the neighbourhood broadcasts message (1) $M_{\text{Hello_candidate}}$ that contains the information related to (node ID, speed, node coordinates and ability to route data and connect to the roadside or cellular). Depending on the available nodes within the Line of Sight (LoS), each node receives the “hello packet” of all other nodes (see Figure 4-6). When the packet is received by each node, the vehicle distance D based on the received coordinates of each node, average speed \bar{S} , and $RSSI$ are calculated at each node.
 2. Upon receiving the information from the other nodes and calculating the D and \bar{S} , message (2) M_{Ack} is the acknowledgement transmitted back by each node along with its average \bar{D} values, speed variance S_{Var} , and \overline{RSSI} . This message is to notify the node about receiving the data and being part of the fitness model computation for electing the head node of the group.
 3. As per the information collected from each node within the transmission range, the election fitness model will be running on those nodes that have received the aforementioned data. Message (3) M_{FCH} is broadcast among those nodes along with their fitness values. Hence, each node will have the values of the fitness model of the other nodes stacked so that it can be compared with its own value which is based on what the election triggers.

4. The node that has the highest fitness value is the winner to be elected as the head of the first group of the tree structure, and to be switched to a gateway function and assigned as the cluster head (CH). Subsequently, the nodes will be notified about the outcome of the election by broadcasting the node ID of the elected node to them; message (4) M_{CH} performs this action.
5. This process attempts to select the number of nodes that connect to CH and to become router(s) level one (R1) based on the fitness values stored on CH to identify the eligible nodes; message (5) $M_{CH_nominated-R1}$ performs this action.
6. The selected nodes that have the best connectivity with respect to CH then transmit acknowledgement of connectivity with their node ID and router function is enabled on those nodes; message (6) M_{R1-CH_ACK} performs this action (see Figure 4-6). However, the nodes that have poor connectivity will be unconnected and in a discovery status.

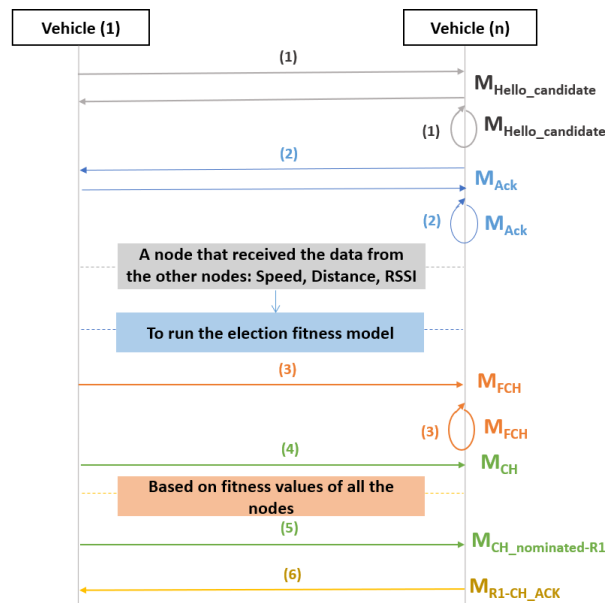


Figure 4-7 The sequence diagram (UML) for the communication dialogue among the nodes for the election process.

- **Establishing the multiple levels of connectivity process:** based on CH election process, the stored fitness values are utilized to identify the nodes that are close to it for establishing the connectivity [19]. The history of data based on “Hello packet” and the internal computation among the nodes including the fitness model can be utilized to form the tree automatically. This process is identified by

the number of levels(hops) of the network which can relate to node capacity and stretch of the road. The nodes participated in the process are configured with router function to be able to establish a given level. Herein, the number of capable nodes is important to the process and thus the total number of hops. The following communication messages are related to the tree levels of connectivity:

7. As R1 nodes are assigned, each has different fitness values stored in its buffer. Each will check the buffer and look into the nominated nodes that are eligible for establishing connectivity by sending message (7) $M_{R1_nominated_R2}$. As a result, each R1 is connected to multiple nodes that have the router function capability to switch to router level two (R2).
8. Those nominated nodes acknowledge the connectivity by transmitting message (8) $M_{R2_R1_ACK}$ to their R1 nodes. Hence, level two of the tree structure is established (see Figure 4-7).
9. Based on the number of nodes that are within the transmission range and the road structure, the levels of connectivity could be created. If few nodes are left for connectivity with certain criteria, then they could be leaf nodes seeking connection to a router. Hence, each R2 node tries to reach the unconnected nodes by sending message (9) $M_{R2_nominated_LF}$ considering the fitness values stored in each R2 node.
10. Accordingly, the nominated leaf node(s) acknowledge the connectivity by transmitting message (10) $M_{LF_R2_ACK}$ to each R2 node (see Figure 4-7).

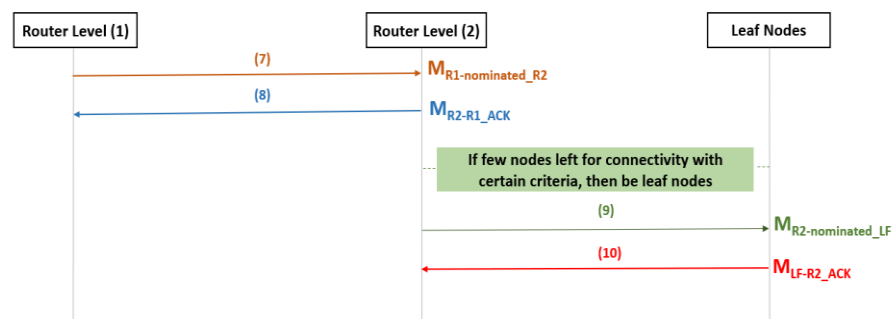


Figure 4-8 The sequence diagram (UML) for the communication dialogue among the nodes to establish the multi-hop.

4.6.2 The Self-Leaving Phase

This process is part of the vehicular grouping mechanism wherein a node configured with a given function leaves the network due to being faulty or because its level of speed has changed compared to the other neighbouring nodes. The impact of a node leaving the network is related to its function as:

- **Leaf node:** its departure will not affect the group connectivity as it is the end point connection but its parent node, the router, should update its number of connections (capacity and occupancy) after the node's departure. The following communication messages will take place between the leaving leaf node(s) and their router connection:
 1. The leaving process is initialized by the leaf node(s) that is departing the network. The node(s) will send message (1) M_{Leaving} to its connection (the router node). This message has the information about the Node ID, current Speed, and RSSI.
 2. The router will then send message (2) M_{Ack} acknowledging the received information. Upon receiving the "*Leaving_msg*", the router will update its current capacity.

- **Router node:** this will affect the group connectivity as it is the main connection of the group depending on its level within the network. The leaf node(s) or/and router node(s) that is connected to it will be left without a main connection. Hence, a replacement node needs to be elected triggering the initialization of the self-healing process. The following communication messages will take place between the router node that is leaving and associated connections:
 1. The leaving process is initialized by the router node that is leaving the network (event trigger). The node sends message (1) M_{Leaving} to its connected child nodes (leaf and router nodes) and also to the routers of the same level (router of other clusters). This message also will be passed to the gateway to trigger the event response that is part of the self-healing process.

2. The leaf nodes and the router nodes then send message (2) M_{Ack} acknowledging the received information. This is explained as part of the event trigger in Section 4.6.3.

4.6.3 The Self-Healing Phase

The factors that necessitate the dynamic self-healing phase to be triggered are associated with the functionality of the node be it a router or/and gateway node, and the node level. Herein, the rank of the departed node in respect with the group, such as a departed head node located in level 1 (L1), level 2 (L2), etc. depending on the number of hops of the network, plays an important role in the need of network self-healing. For example, a departure of a key network-connectivity component located in L1 can impact the group creating rupture in the data communication network operation as the other below levels connected to it. On the other hand, a departure of a router node located in the last level of the network, for example L4, may only cause a partial disruption to the network. It is worth mentioning here that the parallel hops (multiple router nodes with connections) can be located in the same level within the network. The departure of any router node could disturb the network operation in case of multi-levels connected to it. On the other hand, the existence of a parallel hop can assist in the election process and can be elected a node replacement (if it is the best fit node) when the neighbouring router node departs the network.

When the head node departs and leaves its dependent children or leaf nodes unconnected, the self-healing phase will be triggered as based on the above-mentioned factors. This means a new router/gateway node should be elected to replace the departed one and be able to accommodate the unconnected ones. Network re-organization to recover from this situation could involve the cloud looking at the virtual structure and electing a potential replacement (i.e., the fittest possible vehicular node). For this purpose, an operational communication dialogue and fitness model for electing the best-fit replacement vehicular node with minimal or no disruption to the network have been proposed as part of the self-healing phase.

4.6.3.1 Router Fitness Election Model

The objective of this model is to facilitate the election of a replacement eligible node to the departing router/gateway. A number of measured parameters that help in preplanning, allowing for routers load balance and ensuring reliable connectivity are utilized in the proposed approach [24]. The parameters used are discussed in the following:

a) Pre-Election Parameters

- **GPS data (or GIS route plan):** GPS is assumed to be used for route planning and end-to-end journey guidance. It could offer an estimation as to when the departing node is going to leave the network. Such information helps plan-ahead of node departure time and allows for the option of delay tolerance in re-orchestrating the network before the rupture in the network takes place.
- **Vehicular Speed:** This data in conjunction with GPS data is used to calculate the time available before departure. Alternatively, this information can be used to calculate at what distance should the information pertaining to initiating the process of re-orchestration be broadcasted.
- **A Record of the Associated Nodes Addresses:** The departing router possesses updated record of the associated nodes (i.e., an updated list of vulnerable child leaf nodes). Such nodes, if reachable by the gateway or the router at one level above the departing router, are notified by the gateway to participate in the election process. Herein, the nodes can compete with the same level routers to replace the departing router. If unsuccessful, they need to be associated with an alternative router.

b) Election-Decision Making Parameters

- **Distance of the Potential Router from routing path to Gateway:** Herein, sensed RSSI values are used directly as a mean of connectivity signal strength and hence covering for the need for calculating the distance. All routing enabled nodes present their RSSI to the gateway or related upper-level router. This, in effect, presents a more realistic means for connectivity.

- **Distance of the Potential Router from the Departed Router's Leaf Nodes:** The eligible router nodes in the election process, including affected leaf nodes within the reach of upper layer router or gateway, as well as router nodes of other clusters attempt to check their RSSI values with respect to the affected leaf nodes beyond the reach of the gateway. Such RSSI-based checking of connectivity enables identification of the unreachable leaf nodes which could be accommodated by a certain router node and thus, could get re-connected to the network.
- **Ability of a Router to Cover Maximum Number of Affected Nodes:** The potential departing router replacement node should be capable of encompassing as many affected leaf nodes as possible. Herein, the number of affected leaf nodes that could be connected to the candidate nodes can be determined. The affected leaf nodes would set the priority of connection to the potential node through the distance. Affected leaf nodes with RSSI below a threshold value, with respect to a particular candidate node, will not be able to connect.
- **Battery Level of the Potential Router Node:** The battery level of the potential nodes has also been considered as a parameter in the election process even though the energy aspect may not be of much concern in vehicular network. It may be of more significance in other mobile objects like bikes or other subjects carrying wireless smart devices.

The model for the election process attempts to identify a replacement router node among the leaf nodes when the current router departs the network. The focus will be on those nodes that can communicate with the upper level to the departing router or the gateway node, wherein they have been identified as reachable nodes. The competition here will be among the reachable leaf nodes. The fit elected router *FER* based on the above parameters can be described in (4-5):

$$FER = (N_w [RSSI_{RL-GW} + RSSI_{RL-L} + C_{CL-RL} + B_{RL}]) \quad (4-5)$$

wherein $N_w = W \times f$, f represents the fiddle factor pertaining to the respective variable, $RSSI_{RL-GW}$ represents RSSI for reachable leaf node with respect to upper-level router or gateway. $RSSI_{RL-L}$ represents RSSI for reachable leaf node with respect to other leaf

nodes. C_{CL-RL} represents the number of leaf nodes that are reached by the contested leaf. B_{RL} represents the battery level of RL.

In the above model, the fiddle factors corresponding to each of the parameters have been formulated independently to attain uniformity of weightage (normalized values) assigned to each of the variables under consideration (and their final summation).

4.6.3.2 Communication Messages during the Route Recovery Process

The departing router node in the vehicular network is the main trigger for the sequence of messages among the participated nodes in the replacement election process. Each node disseminates its message according to chosen parameters so that the gateway node can start running the fitness model based on the selected criteria to elect one of the eligible nodes. The description of each action undertaken by the various nodes to disseminate their messages is provided as follows [24]:

1. The departing router node identifies that its vehicle will depart the cluster after predefined distance as declared by the GPS measurements. The departing node then collects the vehicle speed and calculates the time remaining prior to departure. It then disseminates the necessary information pertaining to its departure, viz., remaining distance, time, current speed and associated leaf nodes' (children) addresses. Departing router message, M_{DR} (message 1) is as depicted in Figure 4-8.
2. Upon receiving the above information from the departing router, the gateway vies to check for, and subsequently establish connection with the departed router's leaf nodes (children). For this, it broadcasts message 2 M_{GW-L} (see Figure 4-8). This message intended to measure the individual nodes' RSSI with respect to the upper-level router. It will help in identifying the reachable leaf nodes via encouraging a response from each such node. Message M_{RL} is acknowledgement transmitted back by the reachable leaf nodes (along with their respective RSSI values). In response, the gateway or upper-level router transmits an acknowledgement message, M_{GW-RL} notifying the reachable leaf nodes of their participation in the election process (see Figure 4-8).

3. Routers other than the departing router test their reachability with respect to the departing router's leaf nodes. They then notify the gateway on the number of reachable leaf nodes and their addresses, the number of existing leaf nodes that they are currently taking care of, as well as the average signal strength with departing routers leaf nodes. The messages M_{R-RL} , M_{RL-R} and M_{R-GW} are the related messages 5, 6 and 7 respectively (see Figure 4-8).
4. Leaf nodes that could become routers disseminate signals to all departing router's leaf nodes in an attempt to identify those with whom they could establish connection. Again, the RSSI values are considered for the identification of the connectable nodes. This information will then be passed to the gateway. The Messages M_{RL-L} , M_{L-RL} , and M_{RL-GW} respectively perform these actions as depicted by the three messages 8, 9 and 10 in Figure 4-8.
5. As per the information collected from the reachable nodes and other routers, the gateway will work out the fitness values for each of the participant nodes and elect the one with the highest fitness value. Subsequently, all participant nodes will be notified about the outcome of the election by broadcasting the node ID of the elected router to them. This message will also contain information about the leaf nodes for which the elected router bears responsibility.

The process attempts to elect a reachable node that connects to the maximum number of leaf nodes. Messages M_{GW-RL} and M_{GW-R} notify the elected reachable node to take responsibility of the leaf nodes within its range, including the router(s) that could cover the remaining leaf nodes. Messages 11 and 12 cater for these, respectively.

6. Owing to the assignment of the leaf nodes to a new router(s), the relevant routers notify the related leaf nodes and resume their connectivity within the network in accordance with the new arrangement.

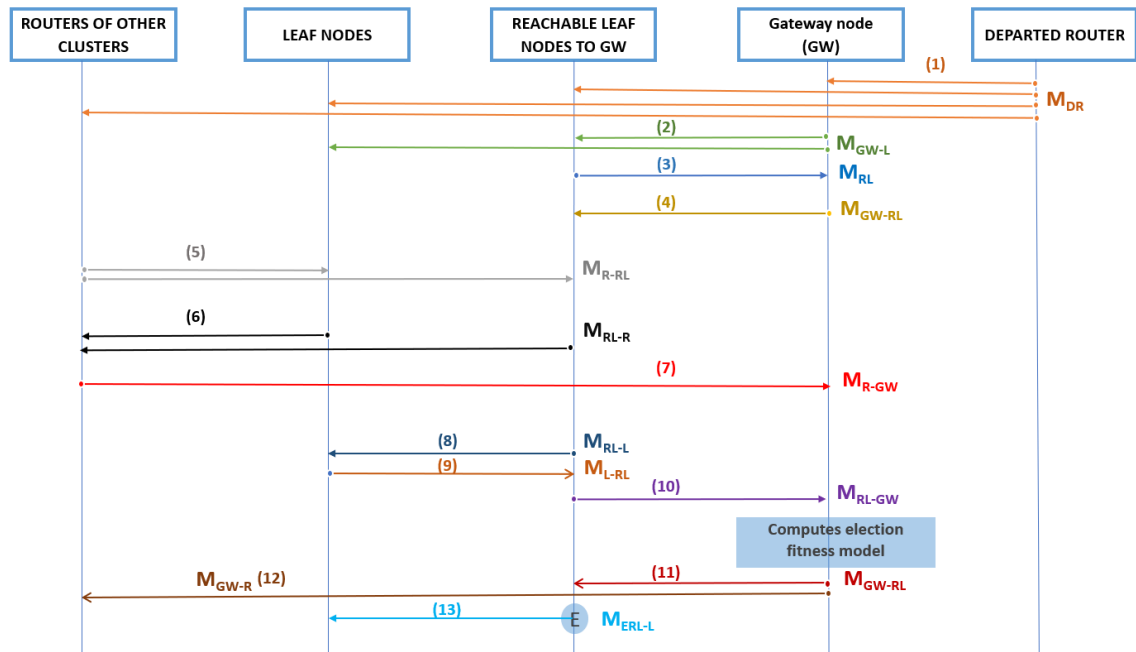


Figure 4-9 UML diagram for the sequence of messages among the participated nodes in the election process.

4.6.4 The Self-Joining Phase

The process involves parameters relevant to the possible candidate router node to be selected for connecting a leaf node that can be part of the network. A joining process model that facilitates the competition among the eligible router nodes is also involved to achieve effective selection with a load balanced network. In addition, the communication messages within the process are disseminated based on stages starting from the connection discovery and ending with the best selected connection.

The Parameters of Selecting a Router Node

The approach utilizes various types of parameters that assist in the node discovery, group load balance, and network maintenance. The parameters used are discussed in the following:

- **RSSI**: this is to determine the radio signal strength when there are two router nodes or more in the same level of the network, but each has different RSSI value in respect to the leaf node that wants to join.

- **Router node level:** this is a connectivity preference related parameter indicating the length of the network in terms of number of hops and the location of the router within the network.
- **Router node occupancy:** the number of connections (the nodes that are connected to a router) is an important factor to set a load balanced group. Herein, a fully occupied router will be in a status of saturation (not accepting other connections).
- **Speed:** this parameter can evaluate the stability of a router node in terms of its speed which can be related to the speed of the leaf node. Herein, a leaf node can set the priority of connecting to a router node with stable speed.

The Joining Process Model: A Priority-Based Node Selection

The model attempts to identify the eligible router node to set the connectivity with the unconnected leaf node. The focus here is on all the router nodes within the established multi-hop network to participate in the joining process. The competition here will be among the router nodes that have the capability to get more nodes connected to them. The model for the router node selection is described in (4-6):

$$N(\text{Join}) = W1 * R_{\text{Level}} + W2 * \text{RSSI} + W3 * O + W4 * S. \quad (4-6)$$

The priority of a node to become a connection to a leaf node (parent node) is determined by its suitability value, $N(\text{Join})$, which is computed based on the mentioned parameters (measurements) wherein each is given weight (W) depending on its importance for the process. The node that has got less occupancy (O), located in a level/hop (R_{Level}) that is close to the unconnected leaf node, good RSSI, and stable speed (S) should be more qualified to be a winner for establishing the connectivity.

The Communication Messages Dissemination Stages and Rules

The communication between the unconnected leaf node(s) and the unsaturated router node(s) (the occupancy is not full) located in the various levels of the established multi-hop network is based on a set of messages that needs to be disseminated to get the leaf node(s) joining the network. The participated nodes disseminate their communication messages based on two stages as described below:

a) Neighbour discovery phase

The unconnected leaf node(s) is in a process of discovery to join the network. Herein, the node is on the “waiting” status until the communication process is triggered by a router node as follows:

1. The router node(s) initiate this process to avoid the other connected leaf nodes of the other routers to interfere in this connectivity. The router node(s) located on different levels of the network send(s) message (1) $M_{\text{Hello_Join}}$ to the unconnected leaf node(s) and allocates a window of time for listening to external nodes that want to join if the router is unsaturated by scheduling the time of connectivity. Herein, the factor of “Request_Time” is a crucial element for the process to eliminate the latency of the process in discovering a connectivity, solve the broadcasting storm issue, and to save the energy of the router node. The router node sends the message within a timer of (2 seconds for example) to receive Ack message from a leaf node. The router will stop sending the message if there is no response and hence it initiates a “Stop_Timer” for (1 second for example). The router node then resumes its discovery by sending the message (1) within the allocated timer. The message (1) $M_{\text{Hello_Join}}$ contains node ID, RSSI, Speed, Router Level, Occupancy.
2. One unconnected leaf node or more could receive the message from one router node or more and hence the leaf(s) sends back message (2) M_{Ack} acknowledging. Herein, upon receiving the “Hello_msg” by each leaf, the leaf node(s) will work out the joining process model as was described in (4-6).

b) Router node selection phase

Each leaf node will compare the values of the joining parameters involved for the routers that the node received the “Hello_msg” from.

3. The leaf node will send message (3) M_{Joined} to the router node that has been selected based on the joining criteria.
4. Accordingly, the selected router should acknowledge this joining by sending message (4) $M_{\text{Ack_Joined}}$ to the new connection (the leaf node). This message is

important when it comes to a scenario of having a number of leaf nodes that are competing to join the network. For example, there are two leaf nodes and there is a vacancy of one node in one router, but the leaf nodes have selected the same router simultaneously. Therefore, a proper distribution should take place.

5. The selected router node then will acknowledge that the other leaf node(s) has not been selected by sending a confirmation message (5) $M_{Unjoined}$ to recalculate its criteria and try the connectivity with another unsaturated router node.

The above communication messages based on the proposed joining stages are depicted in Figure 4-9.

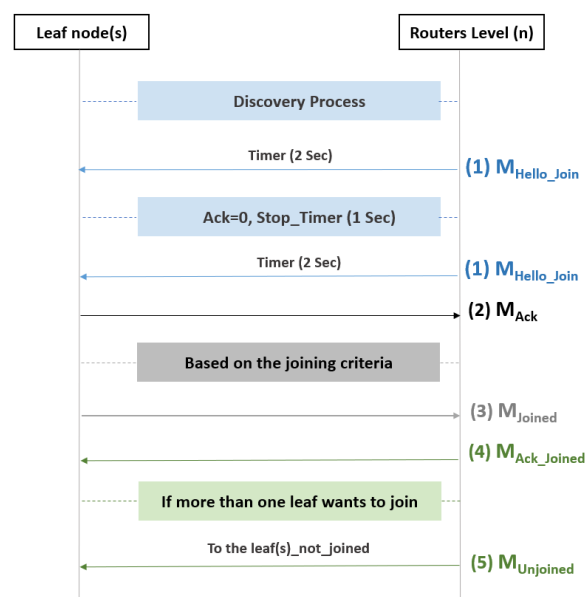


Figure 4-10 The joining process sequence diagram.

4.7 The Road Traffic Model

Based on the described highway traffic scenario in Section 4.2, the road traffic and communication parameters can offer the ideal size of the vehicular group (be it a single hop or multi-hop) from the capacity point of view. The capacity and density of any group on the road can be defined to analyse the group size on a given stretch of the road. Also, the factors of the communication type, number of hops, and type of measurements are the network parameters used for the group size performance analysis.

The lane capacity C_L on a highway road can be calculated based on a given mobile group stretch (boundary) over the road RB , 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 in (4-7):

$$C_L = \frac{RB}{D_{safety}(Ls)} \quad \text{where: } Ls_{min} \leq Ls \leq Ls_{max} \quad (4-7)$$

$$RB_{min} \leq RB \leq RB_{max}$$

in which C_L is the capacity per lane (the maximum number of vehicles that the lane could accommodate within a given RB), 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 entering/travelling along the lane.

In keeping with the context of vehicular group size calculations, the lane occupancy on a highway with, for example, a stretch of 1 km, assuming various number of vehicles on the road, can be calculated in (4-8):

$$O_L = \frac{V_T}{C_L} \quad \text{where } O_L \leq 1 \text{ if } V_T \leq C_L \quad (4-8)$$

in which O_L is the lane occupancy per 1 km, V_T is the total number of vehicles available on the road, C_L is the lane capacity.

Based on the calculated capacity of each condition, the distribution of vehicles for each would vary depending on the total number of vehicles entering/travelling along the lane. The lane density can be obtained accordingly. It is assumed in a multiple lane roading system that the high-speed lane could have the least number of vehicles due to its limited capacity while the left lane (the lower speed) could have a greater number of vehicles. The distribution percentage of vehicles per lane represented by P_L , and the density percentage of each lane as represented by K_L are obtained using (4-9) and (4-10), respectively, as below:

$$P_L = \frac{V_{T(L)}}{V_T} \quad (4-9)$$

$$K_L = \frac{V_{T(L)}}{C_L} \quad (4-10)$$

The total number of vehicles entering the road is represented by V_T , and $V_{T(L)}$ is the total number of vehicles distributed per lane. The random distribution of various cases can be reflected on the vehicular grouping model to evaluate the network structure.

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 on the road, the ultimate road capacity CR_{N_L} can be calculated in (4-11):

$$CR_{N_L} = N_L * \sum_{m=1}^{N_L} \frac{RB}{D_{safety [L_{sm}]}} \quad (4-11)$$

in which $D_{safety [L_{sm}]}$ 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 can be considered as $L_{s_{min}}$ and $L_{s_{max}}$ respectively. This allows ± 10 speed tolerance for the highway road. For the calculations purpose, the minimum road boundary for a vehicular group RB_{min} is assumed here to be 1 km, and maximum road boundary RB_{max} is assumed to be 4 km subjected to the network performance evaluation (discussed in Chapter 5).

Given that the road capacity over a given stretch is defined, the population of a given group is structured as a network needs to be explored. 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 in (4-12):

$$N_{Hop} = \frac{RB}{(TR_{Max} \times K)}. \quad (4-12)$$

The ideal N_{Hop} is dependent on RB 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 $0.1 \leq K \leq 1$. The factor is defined based the received RSSI is higher than a $RSSI_{th}$ constraint. For example, IEEE 802.11p transmission range is up to 1 Km, $RB=1$, $K=0.5$, then $N_{Hop}=2$ hops. The size of each hop $N_{Hop\ (size)}$ in terms of number of vehicles can be calculated based on the road capacity and the obtained number of hops as in (4-13):

$$N_{Hope (size)} = \frac{CR_{NL}}{N_{Hop}} \quad (4-13)$$

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 a 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.

4.8 Communication Network Latency Model

As a given group size can dynamically get structured and re-structured under the various road scenarios such as a lane change scenario, a latency analytical modelling can provide a better analysis for the network simulated in Cooja. Herein, the stages of 'Initialization and Data Dissemination', 'Event Trigger' such as a node departure from the network, and 'Event Response' such as a node replacement are experienced by vehicular grouping. These stages are expressed through a series of communication messages exchanged among the related nodes, and any computation during the process as discussed in Section 4.6. 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 data/packet length; Figure 4-10 depicts how the information is passed from the lower level to the top level, represented by the gateway node. From a packet format point of view, the packet format has an impact on the node selection within each phase of the vehicular grouping approach (such as a replacement router node for the departed one). Hence, every router node within the network, regardless of its level, should have the same packet format, which promotes consistency in selecting a node, be it at a lower or upper level. The size of the packet depends on the communication protocol such as Wi-Fi to offer the appropriate format in which to load the packet with the required data. Within the multi-hop approach, a mixed mode of a given hop dealing with lower-level router(s) and leaf node(s) can be applied. This can affect the packet format that needs to be sent to the upper levels of the network. Hence, the packet format of a router includes the data of its connected leaf nodes and its own data, taking into account the protocol used in the network design to comply with the packet size. As shown in Figure 4-10, node RL1-1

receives the data from RL2-1, and RL2-2 and sends it as is to the upper level. It also generates the packet related to its own data [35].

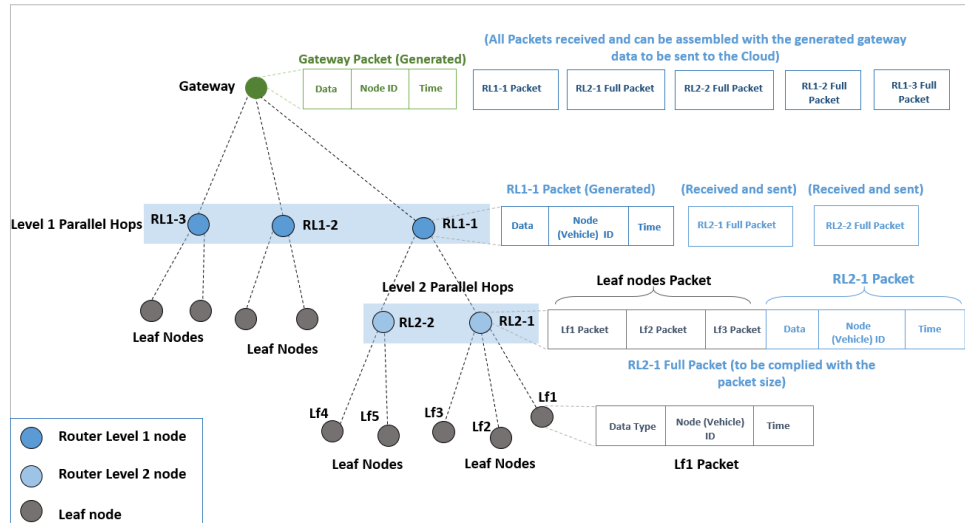


Figure 4-11 The packet transmission along a self-formulated tree structure.

The delay experienced at each level, with the emphasis on the multiple routers within the hop that is called parallel hop, is explained by Figure 4-11 a and Figure 4-11 b. Herein, it is assumed that the delay that occurs in a single-hop (the lowest level), D_{R-Hop} , when the data is transmitted from the source (leaf node) to the destination (router node) is calculated based on the propagation delay within a hop D_{Prop} and the transmission delay D_{TR} . D_{Prop} , D_{TR} , and D_{R-Hop} are obtained using (4-14), (4-15), and (4-16), respectively as below [35]:

$$D_{Prop} = T_{received} - T_{transmission} \quad (4-14)$$

wherein D_{Prop} is the difference between time stamps of the message receipt $T_{received}$ of the destination and transmission $T_{transmission}$ of the source node. In doing so, $D_{Prop-hop}$ can also be increased depending on the number of nodes connected to the router. The transmission delay D_{TR} is calculated as in [126]. However, the propagation delay is considered in our work as it was obtained in (4-14). D_{TR} is described in (4-15):

$$D_{TR} = \frac{P_{length}}{S_{rate}} \quad (4-15)$$

wherein P_{length} is the length of a packet/message transmitted by a node. Herein, P_{length} of a router or gateway node can vary depending on the number of connections. S_{rate} is the communication message transmission rate.

The delay in a hop $D_{R-\text{Hop}}$ is described in (4-16):

$$D_{R-\text{Hop}} = D_{\text{Prop}} + D_{\text{TR}} \quad (4-16)$$

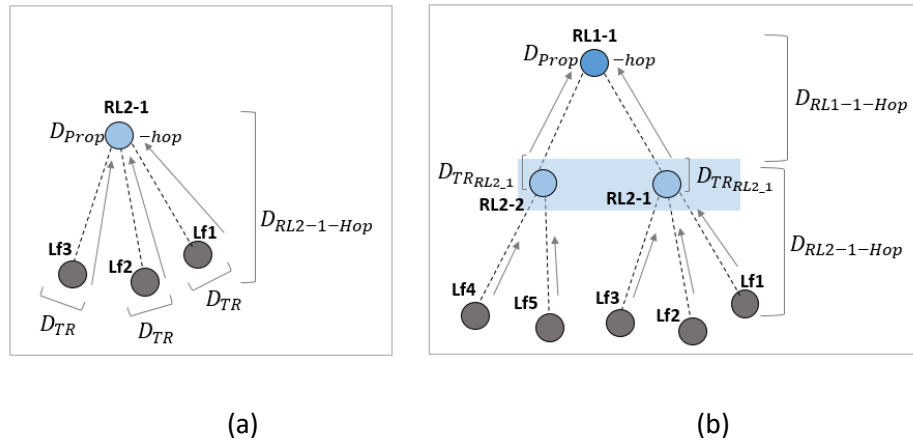


Figure 4-12 The vehicular tree structure packet format and delay (a) delay occurred in level 2; (b) delay occurred from level 2 to level 1.

By assuming the vehicular network-based grouping comprises of a set of vehicles connected by N_{Hop} hops (i.e. $N_{\text{Hop}} = (1, 2, 3, \dots, H)$) offering a multi-hop structure. Based on Figure 4-11b, each level/hop experiences a delay that is different from the other hop. Hence, the delay that occurs when the packet transmitted from the source node traverses multiple hops to reach the destination node (the packet is transmitted from level 2 to level 1, for example) is expressed in (4-17):

$$D_{L2-L1} = D_{\text{Prop}} + D_{\text{TR}(\text{source})} + D_{\text{TR}(\text{mid router})} \quad (4-17)$$

where D_{L2-L1} is the delay from level 1 to level 2. According to the given structure in Figure 4-11b, D_{Prop} is the difference between the received time of the destination (RL1-1) and the transmission time of the source (Lf1). Herein, the received time of RL1-1 is affected by the connected nodes transmission time of RL2-1 and RL2-2. It is worth mentioning here that multiple routers per hop as well as the payload (number of connections) of each router play an important role in calculating the delay. Both of $D_{\text{TR}(\text{source})}$ that is

the transmission delay of Lf1 and $D_{TR(mid\ router)}$ that is the transmission delay of RL2-1 are calculated in (4-15). The delay varies in each level/hop as each router located in each hop has different payload.

An event could take place in the vehicular group that causes a latency that needs to be analysed. For example, the self-healing phase is one of the crucial processes that can take place at any level of the network. The latency in executing the healing process is highly important as it leaves some of the network nodes unable to pass their data. Pre-planning using available vehicular routing data is therefore highly important to avoid this blind region. As the stages of the vehicular grouping approach have been mentioned earlier, the 'Event Trigger' stage is defined in the self-healing phase 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 capable node is elected. This phase depends on the entailed delay by the communication messages/packets that are generated and exchanged between the eligible nodes and gateway node, and the computation process time.

Figure 4-12 illustrates the nodes involved in the process when RL1-1 departs from its location. Herein, the departed router disseminates information about its departure to the gateway, RL2-1, and RL2-2. The latency of the 'Event Trigger' D_{ET} represented by the departed router R_D data dissemination is calculated in (4-18):

$$D_{ET} = D_{Prop(D-S)} + D_{TR(R_D)} \quad (4-18)$$

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 transmission time of R_D . $D_{TR(R_D)}$ is the transmission delay entailed by R_D .

The eligible nodes being part of the replacement departed node election, based on their functionality, maximum capacity, and available vacancy, can entail latency in sending the data to gateway causing $D_{TR(EN)}$. The delay entailed by the data received by the gateway $D_{Prop(D-S)}$ and thus processing delay $D_{Process(Fitness)}$ caused by running the fitness model for the eligible nodes result in the total delay entailed by the eligible nodes $D_{Eligible_Nodes}$ during the event response stage. This is expressed in (4-19):

$$D_{Eligible_Nodes} = \sum_{i=1}^n (D_{Prop(D-S)} + D_{TR(EN)_i}) + D_{Process(Fitness)} \quad (4-19)$$

The gateway node (GW) sends the new role of replacement to the node that has a superior fitness value. For example, RL2-2 is the new elected node (EN) that sends a notification of its new role to the affected nodes. The latency for the stage of announcing the elected node ($D_{Elected_N}$) is expressed in (4-20):

$$D_{Elected_N} = D_{Prop(D-S)_{GW-EN}} + D_{TR(Gateway)} \quad (4-20)$$

Then, the leaf nodes of the elected node, and other connected nodes send acknowledgment to the elected node causing $D_{Prop(Ack)}$. Each node sending the (ack) can experience transmission delay D_{TR} . The processing on 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 $D_{Post_Election}$ is expressed in (4-21):

$$D_{Post_Election} = D_{Prop(Ack)} + \sum_{i=1}^n (D_{TR_i} + D_{Process_i}) \quad (4-21)$$

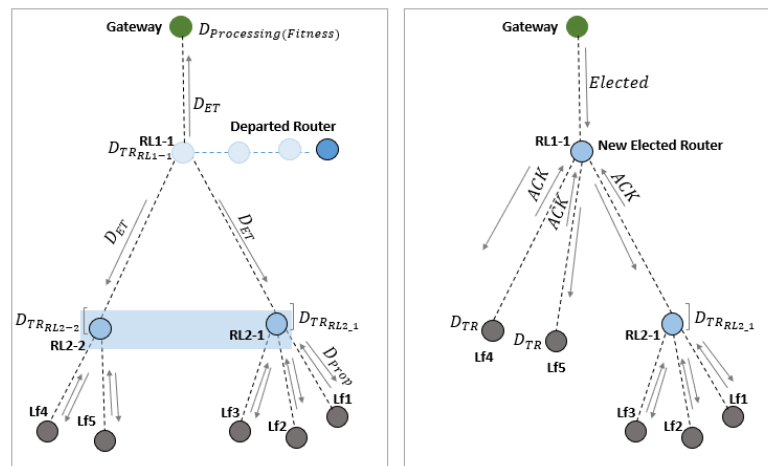


Figure 4-13 The self-healing phase delay.

4.9 Conclusion

In this chapter, the proposed phases of self-X vehicular grouping approach (i.e., self-formation, self-leaving, self-healing, and self-joining) based on a flexible network that can adapt to the dynamic changes on the road is discussed. For example, vehicles leaving the group may rupture the data network and cause fragmentation or isolation of part of the network that raises the need for intelligence for smart healing. The aim of the

proposed approach is developing an effective framework for vehicular grouping that is mainly governed by the road regulations, the size of a vehicular group that is bounded by a given road stretch, number of lanes, and the road type to facilitate data dissemination and route optimization with the ever-increasing data traffic demands. The nodes need to be flexible in approaching the various tasks as well as processing the data through the re-programmability when other tasks need to be prioritized during the network operation. Furthermore, this will offer a platform for studying the various scenarios that support better interaction with road dynamics and help maintaining vehicular movements. Moreover, managing the communication among the group of vehicles on the road promotes the connectivity that is one of the main factors of the autonomous vehicular network.

From the architectural point of view, the vehicular network operating system supported by the IoT virtual cloud environment reflects the overall structure of a cyber physical system. Herein, the modelling is utilized for designing the vehicular grouping algorithm taking into consideration the modelling of each sub process of the solution to then be integrated as a full life cycled grouping approach. The physical network wherein the vehicles are distributed among the lanes following the road regulations is supported by the virtual model in the cloud.

From the vehicular grouping process point of view, the dynamic changes of vehicles on the road require equivalent response in re-organization of the group. This in effect demands the process of initial formation of new groups and on-going healing to any rupture takes place as result of network components leaving the group. New vehicles may join the formulated group considering the proximity of the group while a departure from the network can take place by existing vehicles due to the route changing. To enhance these aspects, the concept of Wireless Sensor Network (WSN) based on three core functions, namely the 'Leaf or sensor node function', 'Router node function', and 'IoT Gateway function' is utilized for our vehicular grouping approach. Each phase of the self-X grouping approach has been looked at from the parameters, fitness election mode, and communication messages point of view.

As vehicular grouping tends to be influenced by the road dynamics and the frequent topological changes, the performance of the network, mainly its response and recovery time, can significantly be affected under the road dynamics. Herein, the performance of the scheme is crucial to be analysed in terms of latency to highlight the required time of the network to go through the phases of self-X (i.e., self-formation, self-leaving, self-healing, and self-joining). 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. For this purpose, a road traffic and latency modelling are designed to support the vehicular group dynamic structure on the road.

Chapter 5 Modelling and Simulation of Vehicular Grouping

5.1 Introduction

This chapter presents the modelling of the vehicular grouping approach based on the WSN three core functions discussed in Chapter 4. The modelling of road traffic and its key involved parameters to set the size of the group that can fit the network and road requirements is also presented. This chapter explores the implantation and testing of the proposed key components of approach as well as the road traffic ideology. For the road, the lane and ultimate road capacity are the main road modelling parameters to be presented in this chapter for designing and testing the group size. Other parameters such as density and distribution are also modelled in MATLAB and tested.

The vehicular grouping self-formation and self-healing, and performance related to the operation of the algorithm were designed using Contiki-Cooja network simulator. The transactional latency, packet loss, and gateway/router node capacity have been utilized for the evaluation of network approach.

5.2 Modelling and Simulation Phases

The modelling of the vehicular grouping approach was conducted based on road and network strategies. Vehicular grouping approach is modelled and developed in Contiki-Cooja tool. The aim was to implement the algorithm based on WSN three core functions i.e., gateway function, router function, and leaf function, in a virtual environment to ensure the operation and performance of the model before the actual physical implementation. Additionally, the tool offers the dynamic re-orchestration wherein the node can switch its role such as reconfiguring a leaf node to act as a router node serving the requirements of the algorithm. Based on the proposed algorithm presented in Chapter 4, the communication strategy and fitness computation components were implemented in the eligible participant nodes. Based on the developed model, a vehicular group was formulated and identified by its size in terms of number of nodes, and number of hops. As the developed group and its on-going dynamics were tested in Cooja, complying with the road through the development of road traffic model and analysis was performed in MATLAB. This offers the identification of the road capacity

and, in turn, the vehicular group size in the road that can be evaluated in Cooja from the perspective of the communication network. Therefore, the relation between MATLAB and Cooja in designing and evaluating the size of a structured vehicular group in the road is reflected by road capacity and network size evaluation. The latency entailed by the formation and re-formation of the network was obtained from the Cooja simulation.

5.3 Road Traffic Model Development and Analysis

The development of the road structure model on which the capacity per lane C_L (the maximum number of vehicles that the lane could accommodate) based on the lane speed, the minimum two-second rule separation distance, D_{safety} , between any two following vehicles within the same lane and stretch of the road, RB, in km was calculated in (4-7) in Chapter 4. The average lane speed, L_s , on a highway is assumed to vary from 80 – 110 km/h. Here, we assume the right most lane is the slowest lane while the other lanes' speed incrementally increases until reaching the left most lane. Hence, in the related road calculations mainly the D_{safety} and lane capacity for a given stretch of the road vary accordingly. The D_{safety} of the four speeds is shown in Table 5-1.

Table 5-1 example Safety Distance for highway speeds.

Lane Speed (km/h)	D_{safety} (m)
80	44
90	50
100	56
110	61

The pseudo-code for defining a group size per lane and along the road using road traffic parameters, such as capacity is as depicted in Figure 5-1. Herein, the input values are lane speed, road boundary, number of lanes, etc., as shown in the pseudo-code. The main calculations involved are lane capacity, occupancy, density, distribution, and road capacity to analyze the road and thus relate it to the network design. These are all set based on the conditions shown in Figure 5-1 [127].

Algorithm 1. Pseudo-code for group size based on road parameters.

Inputs: Lane speed L_S (Km/h), Road Boundary RB (Km), Number of lanes N_L , total number of vehicles travelling along the highway V_T , number of vehicles travelling along a lane $V_{T(L)}$

Initialize Safety distance $D_{\text{safety}}(L_S)$ based on a given L_S

Workout the ultimate capacity per lane C_L using eq. (4-7) & ultimate road capacity CR_{N_L} using eq. (4-11)

for every L_S **do**

if $V_{T(L)} \leq C_L$ **then**

 calculate the lane occupancy O_L using eq. (4-8)

else

 the lane is saturated

end if

end for

for each set of V_T **do**

if $V_T \leq CR_{N_L}$ **then**

V_T is distributed on the road with N_L

if $V_{T(L)} \leq C_L$ **then**

 calculate distribution percentage P_L using eq. (4-9) & density percentage K_L using eq. (4-10)

end if

end if

end for

Output: estimated vehicular group size per lane and along the road

Figure 5-1 Pseudo-code 1 for group size based on road parameters.

From the analysis point of view, Figure 5-2 shows the ultimate capacity of a lane within a given speed based on various RB range from 1 – 4 km. Herein, the lane occupational capacity is increased with the increase of RB. For example, the capacity of a lane with speed of 80 km/h is increased from 22 to 90 vehicles when RB is increased from 1 to 4 km, respectively. This indicates the relationship between various numbers of vehicles and the speed limit of highway lanes within the road stretch, reflecting the estimated number of vehicles in a formed group.

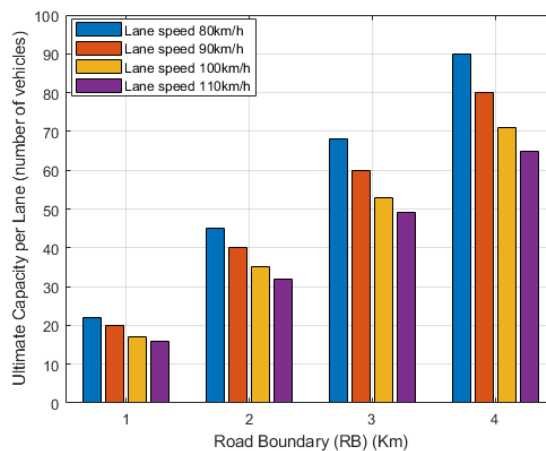


Figure 5-2 The lane vehicular capacity as a function of road stretch.

With the increase of number of lanes N_L , the overall road capacity CR_{N_L} is obtained as based on (4-11) in Chapter 4, in which D_{safety} is dependent on the speed of each lane within the road. CR_{N_L} is one of the road parameters that can have an impact on the possible distribution of number of vehicles on the road. As an example, and for the analysis purposes, L_s is considered as 100 km/h for all the lanes within the road, then $D_{\text{safety}}(L_s)$ will be 56 m, CR_{N_L} can be obtained depending on the set of number of lanes and road boundary as is shown in Figure 5-3. Herein, for example, the ultimate road capacity is 284 vehicles when the road boundary (RB) is 4 km and the number of lanes is 4. Figure 5-3 below clarifies the variation in road capacity in relation to the number of lanes and stretch of the road.

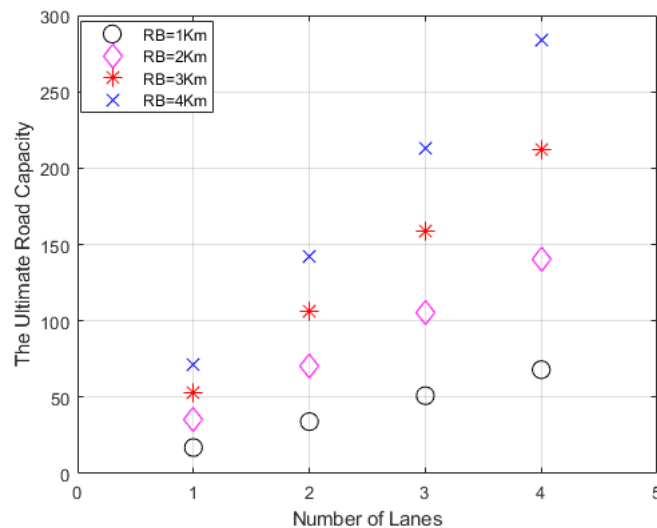


Figure 5-3 The ultimate road capacity.

In keeping with the context of the road structure model parameters, the lane occupancy O_L on a highway with a stretch of 1 km is obtained based on (4-8) in Chapter 4. Having set of number of vehicles travelling along the highway, a lane with a given speed can be partially or fully occupied with vehicles depending on the lane ultimate capacity. This can be shown in Figure 5-4 wherein four various lane speeds range from 80 – 110 km/h, and number of vehicles (5, 10, 15, and 22) moving along each lane are utilized for testing lane occupancy. The lane with speed of 80 km/h is 23% occupied by vehicles from its maximum limit when the number of vehicles entering the lane is 5 vehicles. However, the lanes with speed of (90, 100, and 110) km/h reach to the saturation point (beyond the 100%), as highlighted in red in Figure 5-4, as the number

of vehicles is increased to 22 vehicles. This is due to the ultimate capacity of these lanes as it is shown in Figure 5-2.

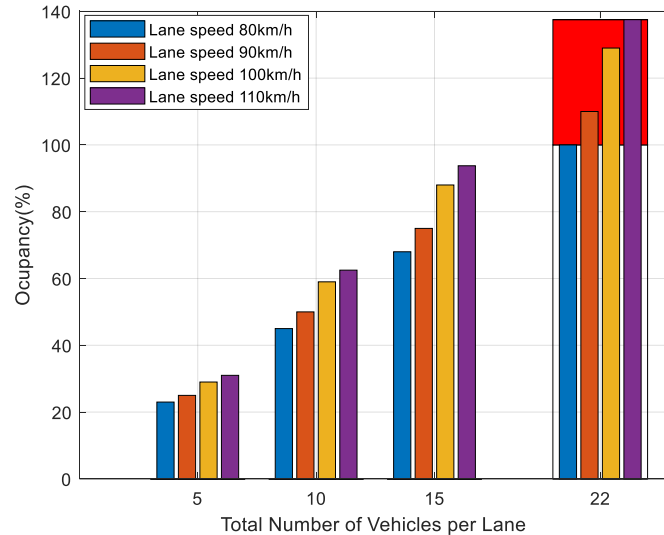


Figure 5-4 The percentage of lane occupancy.

The other road parameters that have an impact on the vehicular network structure on the road are density (K_L) and distribution of vehicles (P_L). Herein, depending on the total number of vehicles traveling on a given highway road stretch that has several lanes with a defined capacity for each lane, the distribution of vehicles for each lane would vary accordingly. Hence, a lane can be less or fully dense. It is assumed in a multiple lane roading system that the high-speed lane could have the least number of vehicles due to its limited capacity while the left lane (the lower speed) could have a greater number of vehicles. Based on (4-9) in Chapter 4 for calculating (P_L), Figure 5-5 below shows hypothesized distribution percentages of vehicles on the road with four lanes. Mainly, a total number of 10-, 20-, 30-, 40-, and 50-vehicle scenarios are considered for distribution on four-lane highway with a stretch of 1 km. The distribution percentage for each lane here takes into consideration the ultimate lane capacity. For example, with 10 vehicles travelling along the highway, 40% of the vehicles can be traveling along the lane with speed of 80 km/h as shown in Figure 5-5. This contributes to 4 vehicles out of 22 vehicles that is the ultimate capacity for this lane. The random distribution of various cases can be reflected on the vehicular grouping model to evaluate the network structure.

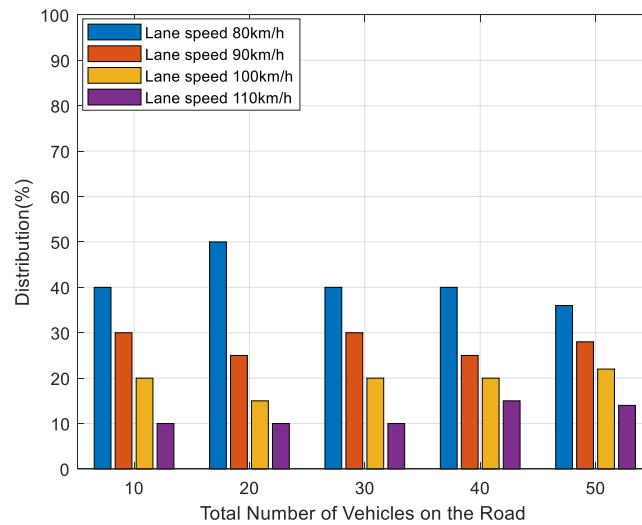


Figure 5-5 The percentage of distribution of vehicles.

Figure 5-6 indicates the density percentage for each lane considering the obtained distribution percentage of the lane that is depending on allocating the number of vehicles for each lane based on the total number of vehicles travelling along the highway. This can be a validation for the possible vehicular grouping structure as the lanes should be less dense to offer the flexibility for the network to perform under future dynamic scenarios. Herein, for example, vehicles can join the formulated group as based on the self-joining approach requiring the network to be below the saturation in terms of density. This can allow the network to have vacancy for the nodes to join its group. As is shown from Figure 5-6 the density percentage is almost 82% for the lane with speed of 80 km/h when 18 vehicles are distributed in this lane out of 50 vehicles traveling along the highway.

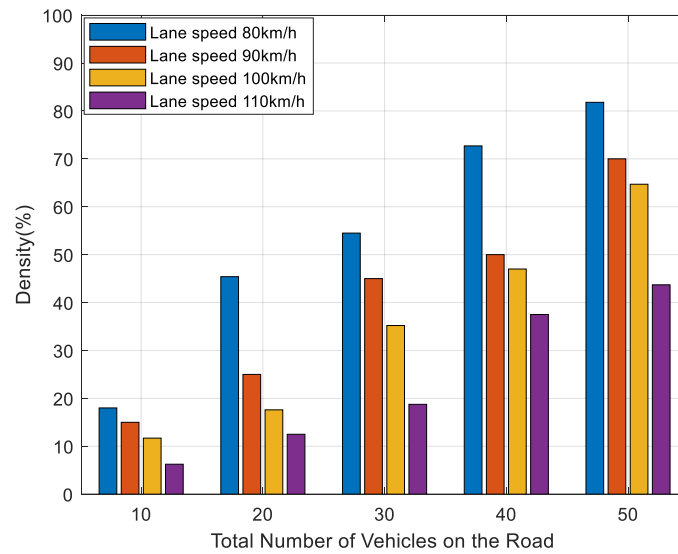


Figure 5-6 The percentage of density.

From defining the number of hops based on road boundary and the transmission range of the chosen communication protocol as discussed and put on (4-12) in Chapter 4, the maximum size of each hop in terms of number of vehicles can be obtained when the road capacity and number of hops are inputs as shown in pseudo-code 2 Figure 5-7 [127]. However, this size is also dependant on conditions within each level/hop such as the type (functionality) of the connections. This can lead to formulating the serial and parallel hops as described in Figure 5-7. Also, the capacity of a router node plays an important role in providing the connectivity to the nodes and thus formulating the other levels as based on the total number of hops for a given stretch.

For example, the maximum size of a hop is 34 vehicles when the road capacity is 68 distributed over 4 lanes with a stretch of 1 km, and the obtained number of hops are 2 hops for the same stretch. Herein, the number of vehicles for each hop could be equal or less than the maximum hop size depending on the node functionality. This is subjected to the network modelling and test.

Algorithm 2. Pseudo-code for the size of hop.

Inputs: Road capacity CR_{N_L} , Number of hops/levels N_{Hop}

Initialize Workout the maximum number of vehicles in each hop as “hop size” $N_{Hop(size)}$ using eq. (4-13)

Initialize Head of level one (HL_1) is one node

Initialize Number of connections (nodes) connected to HL_1 as (NC_{HL_1})

Initialize Number of connections (nodes) connected to NC_{HL_1} (router function only) as ($NC_{Router-C}$)

if $NC_{HL_1} = 1$ **then**
 NC_{HL_1} is either “leaf”, or “router”
 if NC_{HL_1} is router **then**
 formulate level 2 (L_2)
 else network is one level only
 end if
end if

if $NC_{HL_1} \leq N_{Hop(size)}$ of level 1 **then**
 NC_{HL_1} are either “all leaf”, “all router”, or “mix of functions”
 if some or all NC_{HL_1} are with router functions **then**
 formulate level 2 (L_2) with possible parallel hops
 else if NC_{HL_1} are all with leaf function **then**
 network is one level only
 end if
end if

for each Level ($L_{(n+1)}$, $n = (1, 2, \dots)$) formulated after level (1) **do** check
 if one NC_{HL_1} is with router function **then**
 $NC_{Router-C} \leq N_{Hop(size)}$ of L_2
 else if more than one NC_{HL_1} is with router function **then**
 maximum $NC_{Router-C}$ of each $NC_{HL_1} \leq$ capacity of each NC_{HL_1} and
 total $NC_{Router-C} \leq N_{Hop(size)}$ of L_2
 end if
 if $N_{Hop} = 2$ and all the nodes are connected **then**
 a vehicular group with 2-hop is running in the highway
 else
 more hops are formulated
 end if
end for

Output: serial and parallel hops as per each level’s connections and their functionalities

Figure 5-7 Pseudo-code 2 for the size of hop.

5.4 Vehicular Network-based Grouping Model Development

The behaviour of the vehicular network-based self-X grouping approach is modelled using the Contiki-Cooja network simulator. Simulation parameters, such as number of hops are set to design the various scenarios and processes. Table 5-2 depicts the Cooja main simulation parameters taking into consideration the network and road parameters. Herein, the simulation time is chosen as 5 minutes for running the network to generate and collect data. The number of lanes is set to 4 for distributing the nodes in Cooja that is represented by the squares in the simulation window. The other parameter is the number of nodes configured with a given function to perform the main

tasks in the network such as a ‘gateway-capable’ node. This parameter may vary for testing purposes. Other parameters considered in the simulation are sampling rate and packet length, both of which are dependent on the requirements of self-X phases such as the growth in packet length for the tree-approach in self-formation phase. The self-formation and self-healing are considered as core processes for the vehicular grouping that need to be evaluated based on measures like latency and packet loss during the communication. The results and analysis of these processes are discussed in subsection 5.4.1 and 5.4.2.

Table 5-2 Simulation Parameters.

Parameter	Value
Simulation time	5 minutes
Total number of vehicles	30
Number of lanes	4 highway lanes (same direction)
Number of hops	4-hops
Nodes with gateway-router capability	Minimum 6% (2 nodes)
Speed varying	80-110 Km/h

Figure 5-8 shows an example of a Cooja scenario with 8 vehicles distributed on 4-lanes (represented in squares in the simulation window). The number of hops for this scenario are chosen as 4 hops. Three router nodes in level/hop 2 are connected to router level 1 (Router_L1) and two leaf nodes are connected to router level 3 with ID 6 as shown in Figure 5-8.

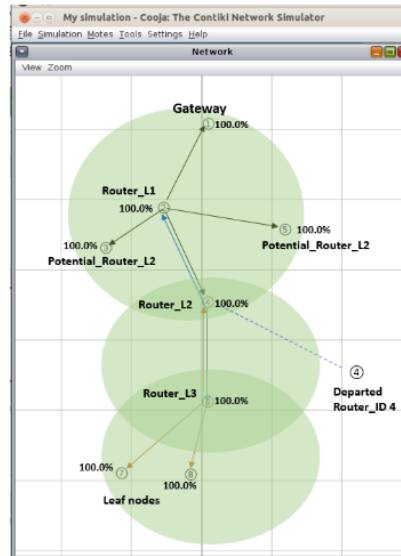


Figure 5-8 Example of vehicular grouping-Cooja network scenario.

5.4.1 Network Self-Formation Modelling and analysis

The vehicular network main scenario model is formulated based on pre-election and post-election processes, enhanced by vehicular-related parameters and the sequence of messages. The pre-election process needs to be analysed to reflect the need grouping approach mainly for calling for 'network formation'. Herein, the Cooja gateway-capable nodes initiate the process by calling for the formation of the group. The data elements are sent in a 'Hello candidate' packet by the nearby nodes. This stage is essential for the network to set the potential number of nodes that will participate in the election process. In addition, the 'Hello' packet includes components that are crucial for the fitness computation [19]. The example pseudo code for some of the 'Hello' packet data such as RSSI and speed is shown in Figure 5-9. The sample code for data transmission, data computation and fitness model components are provided in Section A.2 of the Appendix.

Hello packet

```

float    transmit_of_rssi_wrt_R2_dbl; //to be transmitted
short signed transmit_of_rssi_wrt_R2_intpart;
short signed transmit_of_rssi_wrt_R2_intpart_value=25;

float    transmit_of_rssi_wrt_R3_dbl;
short signed transmit_of_rssi_wrt_R3_intpart;
short signed transmit_of_rssi_wrt_R3_intpart_value=55;

float    transmit_of_rssi_wrt_R4_dbl;
short signed transmit_of_rssi_wrt_R4_intpart;
short signed transmit_of_rssi_wrt_R4_intpart_value=78;
/*-----*/
float    transmit_of_speed_R1_dbl;           //Vehicle speed
short signed transmit_of_speed_R1_intpart;
short signed transmit_of_speed_R1=80;
short signed transmit_of_speed_value_R1;
/*-----*/
float battery_dbl;           //Vehicle battery level
short signed battery_intpart;
short signed battery=90;
short signed battery_value;

```

Figure 5-9 Example of pseudo code for 'Hello' packet.

a) Pre-Election Process Network Behaviour

This stage is based on an un-clustered group, where the communication between the nodes takes place with all the nodes within the transmission range. This could cause data traffic congestion, message loss, and latency in receiving the data due to the absence of a head node that could lead a group of nodes. For this phase, the message received and the latency in communication are the performance measures to be used, reflecting the network reliability and the need for the cluster formation phase.

Based on the literature [128], a variable sampling rate (communication message rate) seems more suitable for occasional disturbance in traffic flow; a lower sampling rate is adopted for stable traffic flow; and a higher sampling rate is required when a traffic disturbance occurs. The network scalability has been tested based on various communication messages rates that are (10, 20, and 30 messages/second), and number of vehicles (10, 20, and 30). It is shown from Figure 5-10 below that the percentage of messages received decreases with the increase in the message rate and number of vehicles. The lower message rates, ranging from 1-10 messages/second, could be a better choice for securing the nodes receiving more percentage of the data [19].

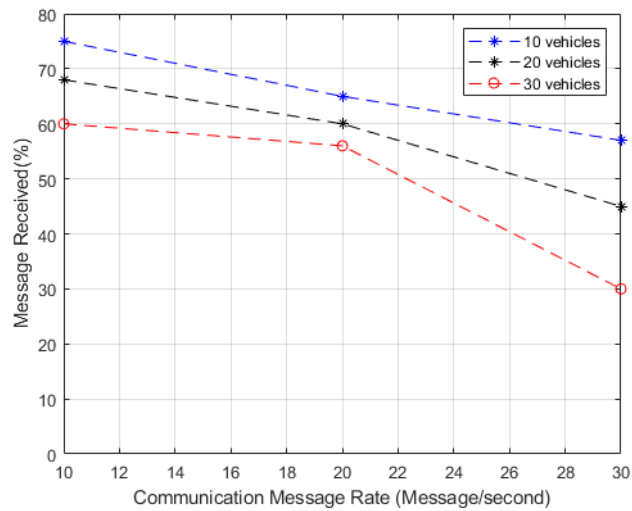


Figure 5-10 The pre-election message received.

Under this stage, the latency in the communication that is both the transmission and propagation delay is analysed based on the time that the node takes to disseminate its data to the neighbour nodes and all the neighbouring nodes are receiving the data (as discussed in Chapter 4 under Section 4.8). Figure 5-11 below shows that with the increase in number of vehicles (5, 10, 15, 20, 25, and 30), the latency in communication occurs due to the ad-hoc flat communication nature among the nodes where the messages are being sent and could be received by every node within the transmission range. Herein, the timestamps in Cooja with the focus on D_{TR} and D_{Prop} (the formulas are discussed in Chapter 4, under section 4.8) were collected to reflect the latency.

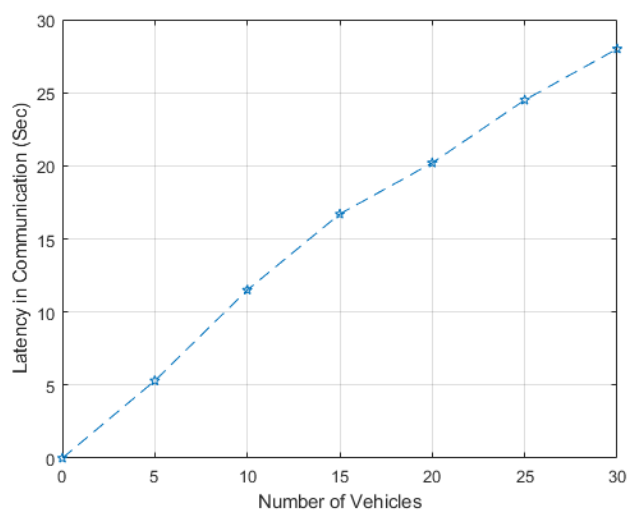


Figure 5-11 Latency in communication.

This pre-election analysis reflects the need for a formation where a dedicated node can act as a receiver as latency in communication can have a better performance. In addition, it shows that it is necessary to configure a given number of nodes (the number of nodes that are performing well) to have the ability to perform the 'call for formation' task.

b) Gateway-Router Capable Node Capacity

The suggested road stretch, and its ultimate capacity based on the suggested highway traffic scenario indicate the possible distribution where the available vehicles within the road may occupy full or partial capacity (as discussed in Chapter 4). Based on that, the number of hops and the time needed for formulating the vehicular network will vary accordingly. The other factor that can influence the structure of the network is the transmission range of the communication protocol where the nodes should be within the LoS to formulate the level(s) of connectivity. The gateway-router capable functional node that is operational under any phase of the vehicular grouping approach is set to have a number of connections (capacity). Herein, the best size of a formulated group is tested through the analysis of the gateway-router node capacity in covering the available nodes using the Cooja simulator.

As indicated by the road traffic model that the road ultimate capacity is 17 vehicles when the speed lane is 100km/h, the set of number of vehicles (5, 10, 15, and 20) is considered. In the Cooja scenario, the communication message rate is considered in the range of (5-40) (message/second). As can be clearly seen from Figure 5-12, the received messages by a gateway-router node connecting five vehicles range from 100% to 80%, whereas the received messages by a gateway-router node connecting ten vehicles and twenty vehicles, respectively, range from 100% to 48% and from 97% to 1%. It is worth mentioning that there is a significant change in the received messages for a head node connecting fifteen and twenty vehicles with 35 and 40 message/second. This could be related to various factors such as communication protocol, simulation time, and the involved parameters such as RSSI that can impact the messages received for the network.

The outcome here reflects the possible size of a vehicular group as well as its boundary in a given hop. The ideal size in this scenario would be a group head node connected to ten vehicles, forming a single-hop group, with a message rate of 1 to 5 messages/second,

with 100% of the messages being received. However, this is subject to the number of available vehicles within the road, and the type of vehicular application wherein the suitable message rate can be chosen [19, 35].

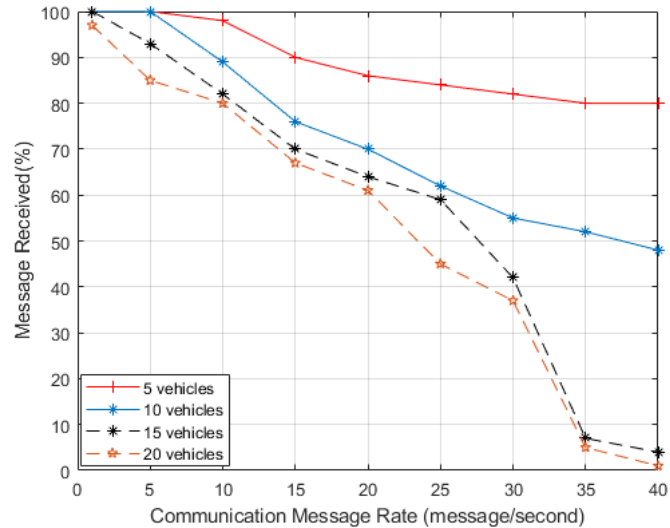


Figure 5-12 The gateway-router capable node capacity.

Upon the analysis of a node connection capacity, using a measure like RSSI to ensure the communication quality within the group (as discussed in Chapter 4 under subsection 4.6.1) plays an important role in formulating the group as well as in structuring the levels of network. This also is related to the use of the communication protocol that is enabled by the nodes in setting the transmission range among the nodes. In Cooja simulation, the transmission range of 200 – 250m LoS is provided for testing purposes and managing the hop(s) that can be correlated to the capacity of a given road stretch.

When a given transmission range in Cooja is applied, the possibility of establishing the communication among the nodes depends on the signal strength of the nodes and the number of nodes available within the space. Figure 5-13 below depicts the result of a Cooja scenario designed to test a number of vehicles under various transmission ranges in terms of received messages. Even though the router node can connect 10 vehicles with good performance as was shown in Figure 5-12, the nodes could be available within the stretch of the road, but with different distances enforcing the need for other router(s) to connect some of the nodes based on multi-hop. This is assumed when the RSSI of a given node is below $-70dB$. As can be seen from Figure 5-13, a group of 15 vehicles with a transmission range of 50, and 100m has message received percentages as 60 and 78,

respectively. Even though this indicates the better performance under a larger transmission range, this is dependent on the RSSI, distance between the vehicles within the stretch of the road, and the number of vehicles. Hence, considering a single-hop group could be challenging for a vehicular network system. Our approach implies the need for having a managed network based on a tree structure where the number of hops should meet the requirements of the protocol range, the distance among the vehicles, and the road stretch. Furthermore, the flow of data within the tree-based structure can be enhanced through a load balanced level of router nodes.

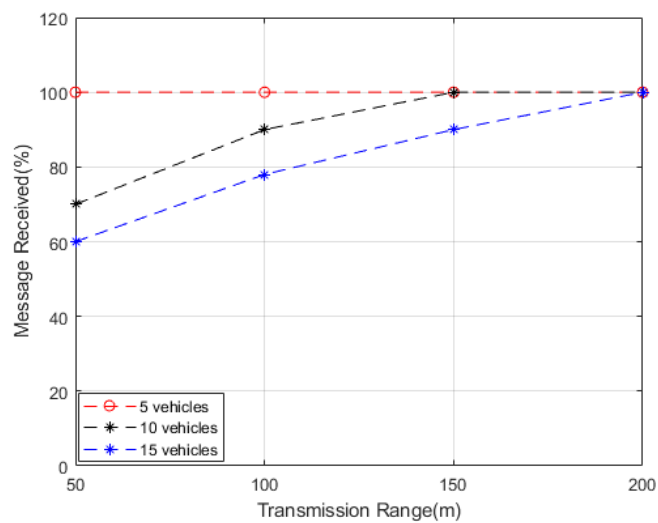


Figure 5-13 Message received based on a given transmission range in Cooja.

c) Hop Latency.

This phase has the stages of initialization and data dissemination represented by the 'Hello' packet exchanged by the gateway-router capable nodes. The 'Event Trigger' stage is when potential nodes are part of electing a group 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 Figure 5-14. This is related to D_{TR} , D_{Prop} , and D_{R-Hop} in the latency model discussed in Chapter 4 under Section 4.8. 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 [35].

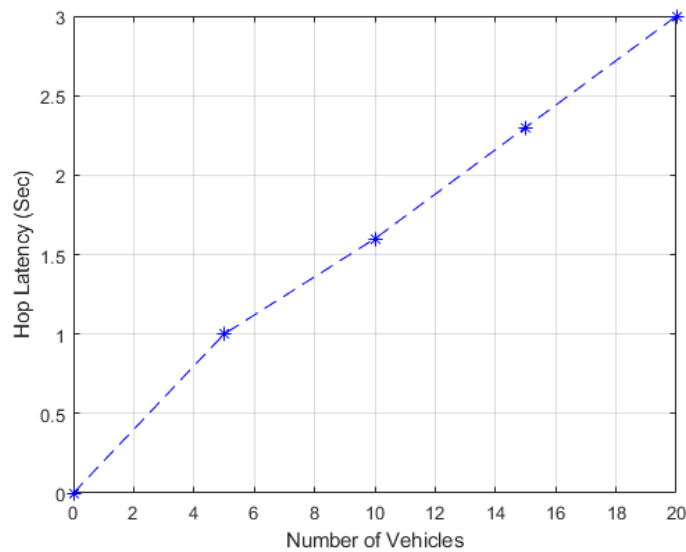


Figure 5-14 Hop latency (router node load latency).

d) Single- and Multi-Hop Network Self-Formation

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 (discussed in Chapter 4), 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 (10 vehicles connected to one router node) as shown in Figure 5-15 [35]. 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 (in seconds) 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 (discussed in Chapter 4 under Section 4.8).

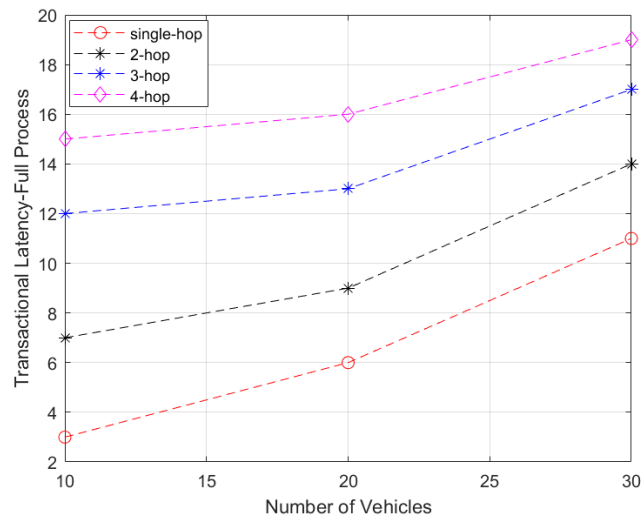


Figure 5-15 The multi-hop self-formation: transactional latency (sec).

5.4.2 Network Self-Healing Modelling and Analysis

The Cooja scenarios are designed for evaluating the self-healing process with the focus on the event response wherein the network can be re-orchestrated. This stage is dependent on the network factors of network size (in terms of number of hops) and the number of the eligible nodes configured with the replacement functionality to be part of the fitness model. Herein, the data transmission of the eligible nodes to replace a departed node and the computation of the fitness model in the gateway unit are highlighted in the C code of Figure 5-16. As can be seen, the data related to RSSI, number of connections (nodes) are disseminated to be computed in the fitness model where the normalized weight of the eligible node is obtained (as discussed in Chapter 4 under subsection 4.6.3). A sample scenario designed in Cooja for a departed router node wherein two of the leaf nodes are eligible to be part of the election process is depicted in Figure 5-17. The network is represented by the nodes of departing router, gateway node, reachable leaf node and unreachable leaf node. The testing and analysis are focused on the consistency of the election and the fitness value of the eligible nodes (whether it stays the same every time the model is running). This can reflect the efficiency of election process in offering the re-orchestration of the network. It also highlights the irregularities in the communication when the eligible nodes encounter situation like being in a blind spot. The analysis with the focus on latency is discussed based on the evaluation of the number of capable nodes during the event response

including the processes of fitness model and when a node is elected and taking the responsibility of the unconnected nodes (resuming the operation of the network).

```



---


Event Response: Fitness Model


---


/**Variables_for_computation_of_election_fitness_model**/
    /**For_reachable_leaf_node_1**/
short signed rssi_rl_GW[16]={0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0}; //RSSI of reachable leaf node with respect to
gateway
short signed rssi_rl_l[16]={0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0};
float c_cl_rl[16]={0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0}; //maximum number of nodes
short signed b_rl[16]={0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0};
short signed rssi_rl_GW_max_range=98;
short signed rssi_rl_l_max_range =98;
short signed c_cl_rl_max_range = 3;
short signed b_rl_max_range =100;
float fiddle_factor_rssi_rl_GW=0;
float fiddle_factor_rssi_rl_l =0;
float fiddle_factor_c_cl_rl =0;
float fiddle_factor_b_rl =0;
short signed instantaneous_sensor_value_rssi_rl_GW[16]={0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0};
short signed instantaneous_sensor_value_rssi_rl_l[16]={0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0};
short signed instantaneous_sensor_value_c_cl_rl[16]={0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0};
short signed instantaneous_sensor_value_b_rl[16]={0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0};

    /*-----SOME OF FITNESS MODEL PARAMETER -----*/
    recv_rssi_wrt_GW_intpart[x] =dataptr_temp_msg_2_to_4[1];
    if(recv_rssi_wrt_GW_intpart[x]>0){
        recv_rssi_wrt_GW_intpart[x]=(recv_rssi_wrt_GW_intpart[x]*(-1));
    }
    printf("\nRSSI value of reachable leaf child node with respect to GW :%d
dBm",recv_rssi_wrt_GW_intpart[x]);
    instantaneous_sensor_value_rssi_rl_GW[x] =recv_rssi_wrt_GW_intpart[x];
    rssi_rl_GW[x] =(100-
((100/rssi_rl_GW_max_range)*(instantaneous_sensor_value_rssi_rl_GW[x]));
    //printf("\nFirst fiddle factor = %f", fiddle_factor_rssi_rl_GW);
    printf("\n1st term = %d", rssi_rl_GW[x]);
    /*-----FITNESS MODEL COMPUTATION-----*/
    normalized_weight_of_rl[x] =(rssi_rl_GW[x]+rssi_rl_l[x]+c_cl_rl[x]+b_rl[x]);
    for (x=1;x<=MAX_NODES;x++)
    {
        if(b_rl[x]>89){
            printf("\n*****FITNESS MODEL COMPUTATION*****");
            printf("\ngateway is computing the normalized weight of the participant nodes.....");
            printf("\nNormalized weight of reachable leaf node %d = %d",x, normalized_weight_of_rl[x]);
        }
    }
}

```

Figure 5-16 The C code of the fitness model.

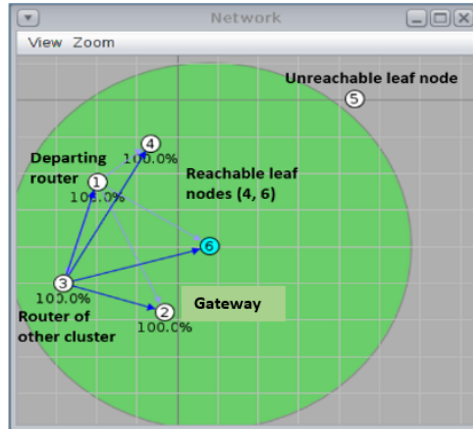


Figure 5-17 Cooja scenario for a departed router.

a) Latency in Event Response

The latency occurred within the event response stage is looked at from the fitness computation process and the announcement of the new elected node to resume the operation of the network. This stage is mainly dependant on the number of the eligible (capable) nodes participating in the election process. For the fitness computation, the analytical latency model discussed in Chapter 4 under Section 4.8 involved the main components causing the delay within this process. After computing the values of the nodes (an example of the nodes values is depicted in Figure 5-18 where node ID 4 is 235, node ID 6 is 255), the node is elected (node ID 6 in the given example) owing to its superior fitness value. The latency entailed by the announcement of the new replacement node and establishing the connection with the child nodes of the departed router is part of the event response and re-orchestration of the network (the analytical latency model of the self-healing phase is discussed in Chapter 4 under Section 4.8).

```

9:18:35.360 ID:2 *****FITNESS MODEL COMPUTATION*****
9:18:35.360 ID:2 Roadside unit is computing the normalized weight of the participant nodes.....
9:18:35.360 ID:2 Normalized weight of reachable leaf node 4 = 235

9:18:41.252 ID:2 *****FITNESS MODEL COMPUTATION*****
9:18:41.252 ID:2 Roadside unit is computing the normalized weight of the participant nodes.....
9:18:41.252 ID:2 Normalized weight of reachable leaf node 6 = 255
9:19:01.252 ID:5 Information '(1) N-DR' received from the governing departing (parent) router is as follows:
9:19:01.252 ID:5

```

Figure 5-18 The outcome of computing the fitness values based on Cooja.

Figure 5-19 depicts the number of 'capable replacement' nodes experiencing latency in 'event response' as part of the competition's fitness computation process. The number of eligible (capable replacement) nodes competing to replace the departed node increases the latency during the fitness computation process. This is due to the propagation, transmission, and processing (running the fitness model) delay, which is explained in Chapter 4 under Section 4.8 by (4-19).

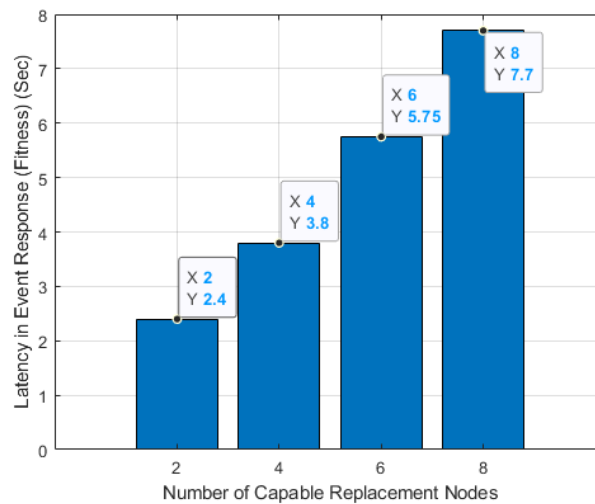


Figure 5-19 Latency in event response (Fitness computation).

Figure 5-20 depicts the event response latency following the election of the eligible node. This includes the latency associated with the gateway announcing the new role to the new replacement node and the new node establishing the connection to the departed node's child nodes. The increase in number of nodes that the new node needs to establish the connection with impacts the latency of the process as discussed in Chapter 4 under Section 4.8. Herein, latency increases when the new node establishes connection with 15 nodes.

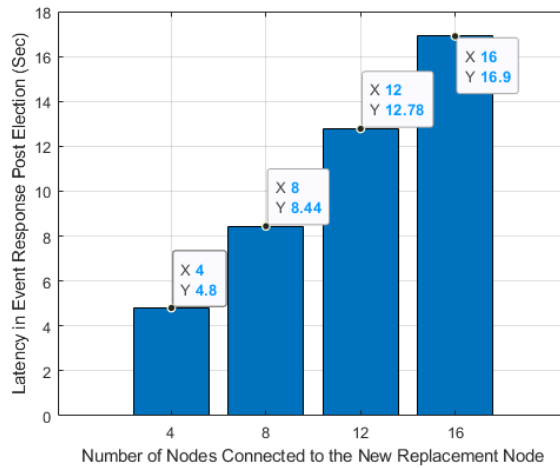


Figure 5-20 Latency in event response (Post Election).

b) The Consistency of the Election Process

The consistency of the fitness model in which the delivery of the fitness computation outcome can be observed in Cooja when the simulation was repeated for 10 times. This indicates if there are any irregularities in the process that may have an impact on the replacement node election and hence the re-orchestration process. Figure 5-21 depicts a comparison of the relative movement and dynamic (significant differences in speed and RSSI values between nodes) scenarios where the election process is repeated for ten trials [24]. During this process, the candidate node has achieved the number of election rounds associated with successful packet transmission 10 times for the relative movement scenario, indicating the process's viability. However, cases where one or more of the candidate nodes are communicating at low RSSI levels or whose transmission is occasionally blocked by neighboring vehicles can have an impact on the process, as shown in the dynamic scenario. In this case, the successful arrival of all critical data may not occur in all operational cycles. Six out of ten, for example, result in the completion of the dynamic operation's election scenario. This type of uncertainty may cause significant disruption to the process, necessitating the addition of backup capable nodes. This may result in latency, as shown in Figure 5-19, but it ensures that the successful election takes place.

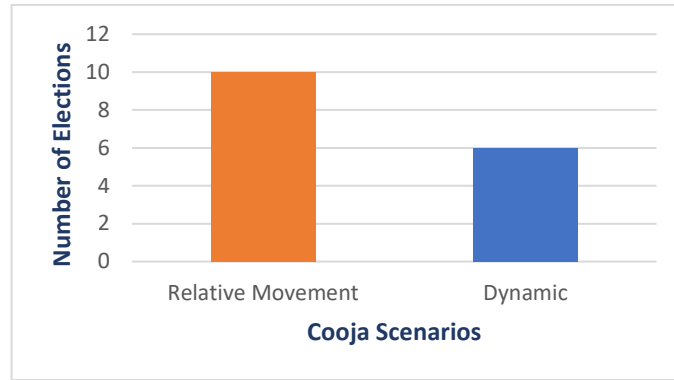


Figure 5-21 The consistency of the election process.

c) Possible communication irregularities

When eligible nodes compete to replace the departed node, irregularities in communication may occur due to signal strength, speed, and so on. An example of two eligible node being part of the replacement node competition, represented by ID 4 and ID 6, reflects potential communication irregularities. In Cooja, various scenarios have been tested in which one of the nodes can be out of transmission range, close to the boundary, or blinded by neighbouring nodes. Herein, due to the irregular movement of the nodes, there is some fluctuation in the packets received percentage in this scenario (whether it is a data or acknowledgement packet). The nodes may loss data, receive partial, or full data due to various movements as is shown in Figure 5-22. For example, upon the movement of node ID 4 and being out of range, the node experiences packet loss. While node ID 6 being within the transmission range receives and transmits the messages, it serves as a backup replacement node and becomes the new replacement node based on the fitness computation [24].

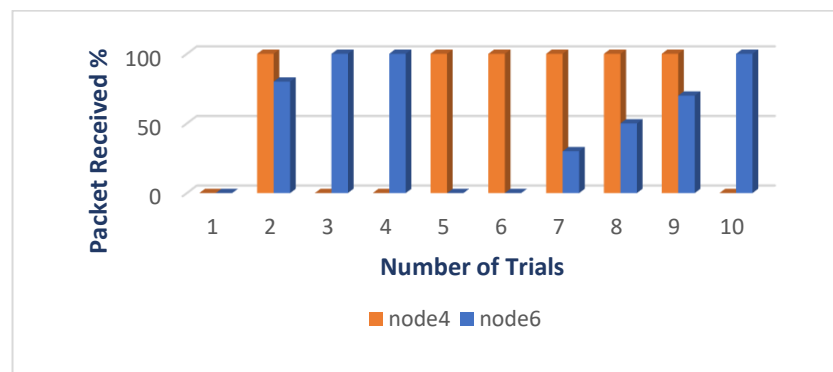


Figure 5-22 Packet received by the eligible replacement nodes based on their movement.

The other scenario reflects the signal strength and its impact on the received packets. For example, node ID 4's connectivity becomes blind due to the presence of an obstacle in the path. Figure 5-23 shows that node ID 4 suffers packet loss due to node isolation, whereas node ID 6 receives and transmits all packets due to its strong signal strength. Node ID 4 can reconnect and receive all packets once it receives a strong signal and its line-of-sight clears. It is clear that node ID 6 receives only 20% of the packets in the last trial of the simulation as the node loses some of the data and acknowledgment messages based on its signal. As a result, as shown in Figure 5-23 [24], node ID 4 is recovering and being elected in the last three trials.

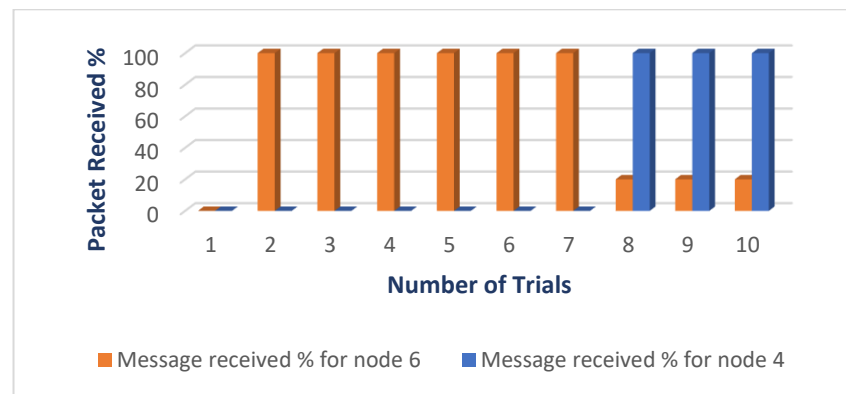


Figure 5-23 Packets received by the eligible replacement nodes based on their signal strength.

5.5 Conclusion

The chapter provided an analysis of the vehicular grouping approach with emphasis on the flexibility of the nodes to assume one or more function for the orchestration and re-orchestration processes. The proposed approach was modelled using Contiki-Cooja simulation tool and analysed based on latency and packet loss. The road traffic model was considered to support the vehicular grouping approach analysis. Herein, focus made on the road capacity, density, and distribution wherein the results obtained reflected the ideal size of a group that can be distributed on the road. This was analysed based on set of number of lanes ranging from 1 to 4 lanes.

From the network point of view, the self-formation based-grouping approach emphasised the function type of the node as gateway, router or leaf function within the network structure promoting a flexible network structure. Both the network

communication parameters and the physical traffic parameters were considered in the fitness model for the tree network formation. The group formation process was tested based on a router node capacity and the number of hops considering the road stretch and its ultimate capacity. This analysis reflects the need of the vehicular network structure to be complied with the road layout. Herein, the data received by a router node with a different set of number of vehicles reflects the possible size of a vehicular group along with its boundary in terms of number of hops. The other crucial performance measure used in network formation analysis is the time of the process based on number of transactions. The formation time of various numbers of hops, along with the different sets of numbers of vehicles available within each hop, was considered.

The other scenarios explored the organization of vehicular network with emphasis on resolving the vehicular clusters self-healing in the event of a routing node's departure. The model was tested based on the latency entailed by different numbers of eligible nodes during the fitness computation process. Also, the latency occurred post-election was considered. The irregularities in communication entailed by the eligible nodes as well as the consistency of the election model were considered based on the packet received percentage.

Chapter 6 Cyber-Physical System

6.1 Introduction

This chapter discusses the use of physical testbed for scenario on implementation of the grouping approach using wireless Texas Instrument CC2538 sensor nodes. From the hardware perspective, the key components for the leaf node and coordinator node (i.e., router or group head), such as communication rate are discussed, mirroring the core aspects that are used in the virtual platform. This interactive collaboration between the virtualization and physical implementation promotes the cyber-physical system. The chapter delves into the aspects of the physical network implementation scenarios setup including the number of nodes, sensing variables, and mobility. The RSSI sensing variable is utilized for the test as it can indicate the relative mobility of the nodes within the group based on the quality of communication. Also, the collected RSSI values based on node mobility can be utilized for detecting the possible departure of a node from its related group based on the distance. This can be used for the virtual network to provide the best network re-orchestration service when needed. The scenarios of testing are focused on evaluating the capacity of the coordinator node based on scalability and sampling rate in terms of packet loss.

6.2 Physical Network Set-up

The selection of hardware to implement any physical network plays an important role in reflecting the ideology of data communication, network topology and a real-life testing scenario. Texas Instruments CC2538 (TI CC2538) wireless module is the targeted hardware for structuring a physical network (as discussed in Chapter 3). The main parameters of sensor data size, sampling rate, network topology, node function, and node mobility have impact on the physical network performance and its possible interaction with the cloud. This mainly is critical for networks like vehicular network (VN) due to the critical events and process dynamics.

A testbed representing the physical network is deployed at Sensor Network and Smart Environment Research Centre (SeNSE) to reflect the main functionality of a given topology such as star and tree network scenarios. A total of 33 TI CC2538 wireless sensor

nodes were configured within the network using Contiki Operating System (OS), of which 30 nodes configured as leaf nodes reported RSSI sensing values within a defined sampling rate and 3 nodes were configured as coordinator nodes (group heads). The physical network set-up for TI CC2538 leaf nodes is depicted in Figure 6-1 a, and the TI CC2538 coordinator setup is shown in Figure 6-1 b. The objective of the physical network setup was to log the RSSI data for each coordinator for 24 hours to provide enough time for data analysis. Herein, the analysis of the collected data was utilized for fetching the minimum and maximum RSSI data to the Cooja virtual model to reflect the modelling based on real data since both the hardware and Cooja motes use the same Contiki firmware. Also, the mobility aspect can be reflected through the change in the RF transmission power of the sensor nodes based on indoor and outdoor scenarios. Furthermore, the mobility can be reflected through the use of battery attached to one of the nodes to measure the RSSI values based on the distance. Moreover, the RSSI data is collected at different sampling rates with various number of nodes scenarios to test the delivery of packets and whether there is any packet loss. This mainly was to evaluate the coordinator node capacity.



Figure 6-1 Physical network set-up in SeNSE lab (a) TI CC2538 leaf nodes.

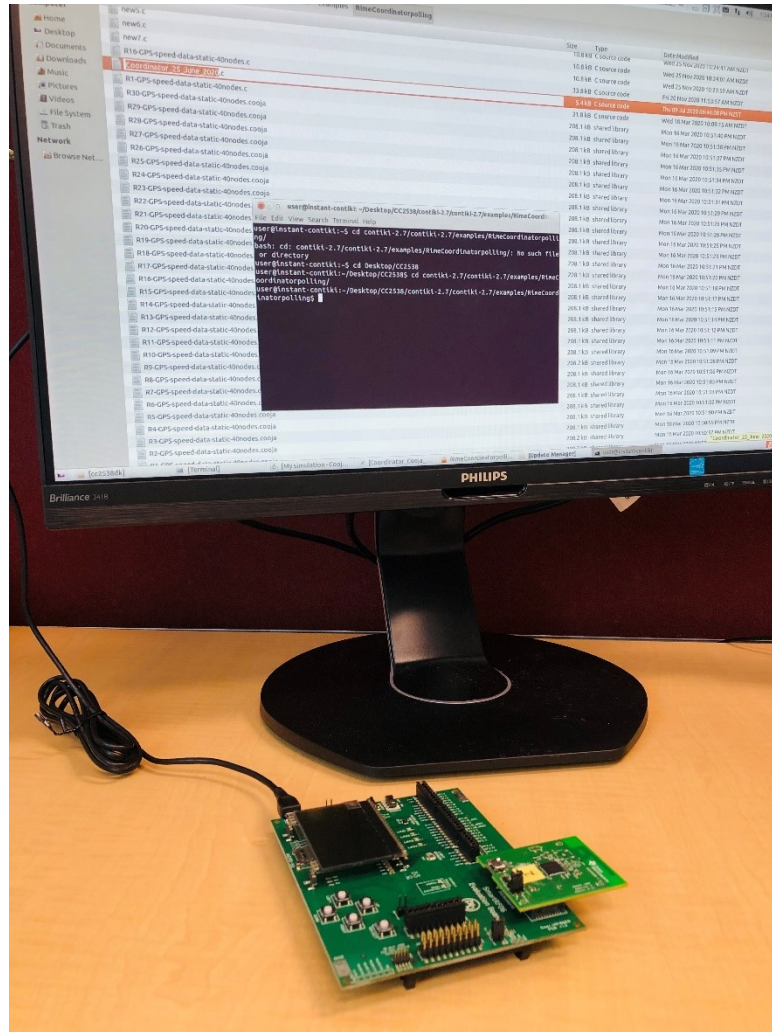


Figure 6-2 Physical network set-up in SeNSe lab (b) TI CC2538 coordinator node for data collection.

6.3 Physical Network Implementation Scenarios

6.3.1 Leaf and coordinator nodes main components and data collection

The 'Contiki OS' generated codes used for compiling and configuring the physical nodes represented by TI CC2538 are the ones utilized for compiling and creating virtual nodes. As a result, the logical part of the operational dynamics of the physical environment can be accurately represented virtually. This provides the flexibility of accessing the physical node code before the implementation through the use of the virtual mote code. The header files, channel allocation, node ID are the main components that are different from the virtual mote (as discussed in Chapter 3 under subsection 3.4.1). The pseudo

codes for some of the main configuration parts of both the TI CC2538 leaf node as well as group head (coordinator) node are shown respectively in Figure 6-2 and Figure 6-3. From Figure 6-2, the RSSI sensing function, communication/sampling rate that can be set using the same function as for the virtual leaf mote (discussed in Chapter 3 under subsection 3.4.1), buffering, and the channel access method at the MAC layer (giving the example of TDMA method in the leaf node) are the main components that reflect the configuration of the leaf sensor node in the establish testbed. It is worth mentioning that the variable 'transmit_flag' is not available for transmitting the buffer for the CSMA method since the 'if' condition within the broadcast function is not required to be set as no specific time needed for the nodes. The 'if' condition is used here to determine whether or not the 'transmit_flag' is set prior to data transmission.

Leaf Node

```

RSSI Sensing Function:
rssi=packetbuf_attr(PACKETBUF_ATTR_RSSI) //to acquire the desired RSSI sensing values

Sampling Rate:
etimer_set(&et, CLOCK_SECOND*SAMPLING_RATE_VALUE) // this function is used for setting the value
of the sampling (communication) rate

Buffering the Sensed Data
c[0]=node_ID; // the node ID is the first element of array 'c'

c[1]=rssi; // the rssi value is the second element of array 'c'

Transmission to The Group Head Node (Coordinator)

packetbuf_copyfrom(&c, sizeof(c)); //transmitting the array 'c'

        broadcast_send(&bc);

Channel Access Method: TDMA
PROCESS_THREAD(cc2538_demo_process, ev, data)
{
    while(1) {

if(Transmit_Flag==1)
{
packetbuf_copyfrom(&c, sizeof(c)); //transmitting the array 'c'

        broadcast_send(&bc);

Transmit_Flag=0;

}

}

}

```

Figure 6-3 Pseudo code for configuring TI CC2538 leaf node.

From Figure 6-3, the declaration of the received data from the nodes connected to it is in an array format. Then, each received sensing data as well as the node ID of the transmitter node is stored individually. Depending on the number of connected nodes, a counter can be set to print the received data from the transmitter nodes. Also, packet

loss can be added to coordinator by setting any condition that can indicate the loss of a packet.

Coordinator Node

Declaration of Received Data in Arrays
short signed rssi[n]=(0₁,...,0_n); // the array of 'n' for receiving rssi data from all leaf nodes connected to this node

Receiving Sensed Variables from Leaf Nodes
//The incoming data from the leaf nodes are stored
int16_t *dataptr_temp1;
dataptr_temp1=(int16_t *)packetbuf_dataptr();
x=dataptr_temp1[0]; //for receiving the node ID of a leaf node
rssi[x]=dataptr_temp1[1]; //receiving rssi data from leaf node 'x' connected to this node

Setting Counter and Printing Data from all The Leaf Nodes
if(counter==number of leaf nodes)
{
counter=(counter % number of leaf nodes);
for (x=1; x<= number of leaf nodes; x++)
{
printf("%d,%d", x, rssi[x]); // printing the rssi received by the leaf nodes
}
}

Packet Loss Observation
for (x=1; x<= number of leaf nodes; x++)
{
if (rssi[x]==0) //setting the condition for considering the packet is lost when the rssi value is not reported by a leaf node
{
counter_packet_loss++;
printf("packet loss = %d", counter_packet_loss);
}
}
printf("packet loss_1 = %d", counter_packet_loss);
counter_packet_loss=0;

Figure 6-4 Pseudo code for configuring TI CC2538 coordinator node.

For RSSI data logging, the data can be sent and received based on the sample codes above. A sample of some of the data collected in text format within Contiki is depicted in Figure 6-4. The received data by the coordinator is displayed represented by the connected leaf node ID and its RSSI value along with the experienced number of packet loss in each round.

```

[1,-55|2,-71|3,-43|4,-49|5,-44|6,-44|7,-55|8,-46|9,-66|10,-64|11,-64|12,-47|13,-52|14,-44|15,-41|16,-48|17,-52|18,-51|19,-54|20,-56|21,-45|22,-56|23,-48|24,-46|25,-41|26,-47|27,-64|28,-66|29,0|packet loss =
'1'30,-61|packet loss_1 = '1'
[1,-55|2,-65|3,-43|4,-49|5,-67|6,-45|7,-55|8,-46|9,-64|10,-66|11,-64|12,-47|13,-63|14,-72|15,-41|16,-48|17,-51|18,0|packet loss = '1'19,-54|20-55|21,-45|22,-57|23,-42|24,-46|25,-48|26,-47|27,-68|28,-69|29,-75|
30,-60|packet loss_1 = '1'

```

Figure 6-5 A sample of the RSSI logged data to text file.

6.3.2 Mobility scenario using transmission power

One of the tests was conducted based on the change of RF transmission power output of TI CC2538 end devices (leaf nodes) based on indoor scenario (SeNSE lab at AUT) and outdoor scenario (around Aotea Square in Auckland) to reflect the signal quality. Herein, the dynamic alteration of the transmission power output of a given node via the C code can test the reliability of communication between the nodes. The intended radio transmission power for the TI CC2538 can be set by entering the hexadecimal value assigned to the selected power mode within the C code. The power output values used for the indoor and outdoor tests are 22dBm RF output power with the hexadecimal value 0xFF set in the power function in the C code, and 7.5 dBm output power with the hexadecimal value 0x42 set in the power function. Figure 6-5 depicts the power function in the C code.

Power function

```

uint8_t
cc2538_rf_power_set(uint8_t new_power)
{
    PRINTF("RF: Set Power'n");

    REG(RFCORE_XREG_TXPOWER) = new_power;

    return (REG(RFCORE_XREG_TXPOWER) & 0xFF); //for 22dBm
}

```

Figure 6-6 Power function in C code.

As based on the selection of the RF transmission power values modified in TI CC2538, the RSSI values for the indoor and outdoor scenarios were logged for three rounds as shown in Table 6-1. With the increase of transmission power, the signal strength in both scenarios (indoor and outdoor) was below -65 dBm. This reflects the reliability in communication and the impact of changing transmission power to assume the distance between the nodes.

Table 6-1 Transmission Power impact on RSSI indoor and outdoor scenarios.

RF Transmission power	RSSI values (dBm) for Indoor scenario	RSSI values (dBm) for Outdoor scenario
22 dBm	-69	-86
	-71	-86
	-67	-87
7.5 dBm	-52	-72
	-55	-78
	-55	-78

6.3.3 Mobility scenario using rechargeable battery

The RSSI sensing values collected from the physical network are of high importance to networks like VN as they indicate the possible departure of a node when it happens to venture outside the communication range of the other nodes. The collected RSSI data can be analyzed to observe any variation of the sensed values. A scenario test based on the network of TI CC2538 was conducted to collect RSSI data from a mobile coordinator node with respect to its leaf node. Herein, the coordinator node was powered by a rechargeable battery (as discussed in Chapter 3 under subsection 3.4.1) to flexibly move away from the leaf node.

The collected data indicates that RSSI values range from (-72 to -94) dBm when the coordinator node moves outside SeNSE lab, reflecting the degradation of the node signal strength. It is worth mentioning that the RSSI sensed values collected from the physical network can be fed into the virtual network for testing and offering an operational network re-orchestration scenario. Table 6-2 depicts the RSSI value of the departing coordinator node that is equivalent to the distance, in meters, of the departed node.

Table 6-2 RSSI values collected of the node movement with reference to the distance.

RSSI values of the departing node (dBm)	Distance of the node moving away (m)
-64	5
-67	6
-78	7
-88	8
-94	10

6.4 The Router Node Capacity Performance

From a network performance point of view, the network scalability scenarios have been explored with the increase of sampling rate to reflect the packet loss measurements. Mainly, the testing can relate to the network connectivity (router or gateway) capacity that was tested in the virtual platform using the Contiki-Cooja simulator. Herein, the physical network test scenario objective is aligned with our road traffic analysis capacity and virtualization capacity testing scenarios (as discussed in Chapter 5). The physical network test is performed, and data is collected when a set of (10, and 20) TI CC2538 connected to a coordinator node report RSSI values based on a set of sampling rates (1, 2, 3, 4, and 5) samples/second. Figure 6-6 shows the total number of packets lost when 10 nodes of TI CC2538 are connected to a coordinator node, 7 packets at 5 samples/second. However, the total number of packets lost increases to 12 packets at the same sampling rate when the number of nodes connected to a coordinator node is set to 20 nodes. Although the physical network has experienced slightly greater packet loss due to real-world factors impacting the quality of RSSI signal such as the network deployment environment, obstacles, etc., the physical test has indicated the importance of having the virtualization for network soft trials.

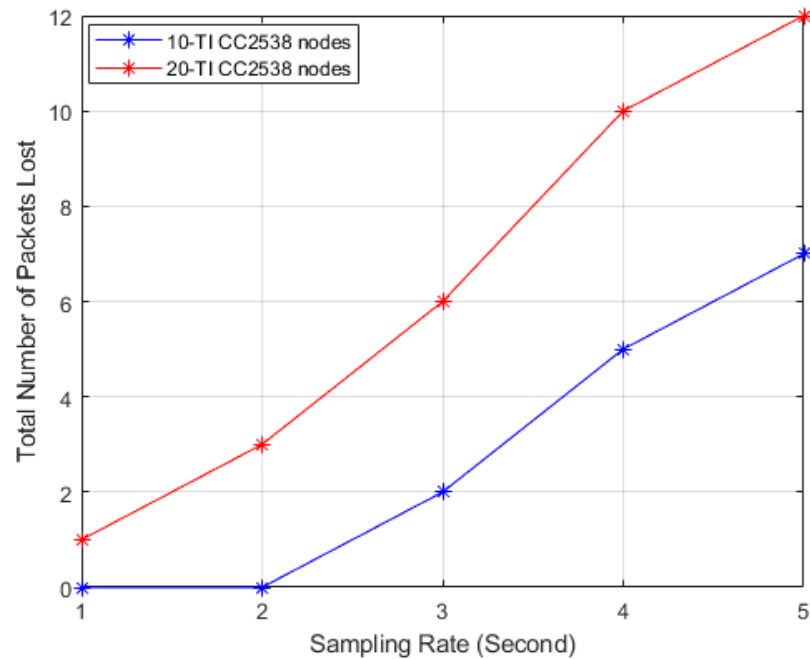


Figure 6-7 Router capacity based on packet loss.

6.5 Conclusion

The chapter provided physical network implementation using commercial sensor node TI CC2538 with the focus on node capabilities and ability to interact with the process requirements. Physical network implementation scenarios with the focus on RSSI data were designed to reflect the mobility of the network with the use of rechargeable battery. This reflected the RSSI values when the node is departing from the network and thus the distances are obtained. Also, the change of the transmission power has indicated the change in RSSI values for indoor and outdoor scenarios. The router capacity was tested based on packet loss and showed slightly more packet loss compared to the virtual network due to the real-world factors such as obstacles. This promoted the cyber-physical network wherein the virtual and physical networks can be interacted.

Chapter 7 Conclusion and Future Directions

7.1 Introduction

The chapter offers conclusions on the main components and findings of the thesis related to the vehicular grouping approach. Herein, the light is shed on the integration of some of the latest technologies such as virtualization and softwarization to offer a flexible vehicular group that can react dynamically to any road event. The future work requirements in looking into the various aspects in the research of a flexible vehicular grouping based WSN, such as the possibility of offering local computations through the edge or the fog without being dependent on the cloud, are highlighted.

7.2 Conclusion

This thesis provided the motivational background behind the topological organization problem of VN and its feasibility to dynamically react to road events such as traffic accidents. Considering the problem domain, the core components involved in constructing a flexible, adaptive, and rapid VN structure that can comply with the road regulations are critically discussed and focused on two key parts.

The first part relates to the road structure and the impact of road parameters on the network topology. The road type, the road stretch, and the number of lanes is the influencing parameters on the size of the network. From the analysis observation, based on the known safety distance of 2-second between each two vehicles, this thesis proposed and suggested a generic analytical model for calculating the road capacity, density, occupancy and distribution of vehicles based on the mentioned road parameters. This has provided an indication of the possible size of the vehicular group that may formulate a network on a given road. The network model also explored the parameters that encourages a given network topology. The hop count parameter, based on the road boundary (road length) and the transmission range of the communication protocol used for vehicle-to-vehicle communication, has provided an indication of the topology as to whether the communication is single-hop or multi-hop. In addition, the size of a given hop is identified by the road capacity and the total number of hops that the network has. While the analytical model emerged from an analysis of road

parameters and traffic engineering principles, the defined, for example, road capacity and network topology based on obtaining the hop count and the size of each hop offers grounds for modelling a communication network that complies in the size and structure with road traffic regulations and parameters and allows for an effective analysis of the dynamic events and the required network response. In the proposed model, the highway scenario with various lane speeds was the main focus in supporting the network topology and size and hence its distribution on the road. The highway scenario reflects the continuous flow and sparse layout of vehicles and offers good potential for the formation of isolated groups, considering the road length [19]. MATLAB is used as the modelling and testing environment. The road traffic model has been analysed taking various scenarios into account. The results using the highway scenario with a given number of lanes, road boundary, speed limits, safety distance, and total number of vehicles travelling on the highway showed that the road capacity has an impact on the possible distribution of vehicles on the road. It is also increased with the increase in the number of lanes and RB. From a lane occupancy point of view, the results reflected that for a road length of 1 km, the lane reaches the saturation point (beyond its ultimate capacity) at a speed of 100 km/h when the number of vehicles occupying the allocated stretch is increased to 22 vehicles. Furthermore, the data analysis outcomes reflected the significance and impact of road structure and regulation on the network topology and the importance of bounding a given network topology size and structure with the road.

The second part relates to the vehicular network structure and the topology used to support the rapid communication between the vehicles and the related entity that offers intelligent computation. An example here is the cloud providing the solution for a flexible IoT-based VN system that responds to the road requirements. This thesis proposed the architecture of an intelligent vehicular grouping based on the self-X phases (i.e., self-formation, self-leaving, self-healing, and self-joining) with the employment of SDVWSN backed up by network virtualization. The core WSN functions are represented by 'Leaf Sensor Node', 'Router Node' and 'IoT Gateway Node'. These are modules that are modelled and tested as software on a virtual platform before the physical implementation. This forms a self-configured network that is similarly formed for the

physical network. The system architecture offers flexibility to VN through software reformulations at the virtual level. The functional role of a given node in the vehicular group is flexibly switched via the implementation of one of three discrete functionalities (e.g. reconfiguring a leaf node to act as a router or gateway node and vice versa) to offer network topology re-orchestration capability and meet the service requirements [19, 20, 24]. The vehicular grouping approach design has been dealt with based on parameters such as RSSI, Speed, etc., and a communication dialogue between the vehicles and the computational unit. Herein, the three stages of "Initialisation and Data Dissemination", "Event Trigger", "Event Response" are part of the structuring of the grouping approach, allowing for re-orchestration analysis if needed. The two main phases that affect the system are self-formation and self-healing due to their importance in offering the core network structure and recovering the network when a service disruption occurs in the network. The approach is modelled and tested on the virtual platform using the Contiki-Cooja network simulator, providing the testing ground for the grouping approach through softwarization before the physical VN is implemented and tested. The performance measures of packet loss and latency experienced in the system are the main measures used for the analysis. For the self-formation phase, the capacity of a gateway-router capable node is tested based on the message received. Herein, set of number of vehicles (5,10,15,20) and communication message rate ranging from (5-40) messages/second is considered for the evaluation. Based on the analysis, a group size of 10 vehicles with message rate of 1 to 5 message/second provides 100% messages received. As based on the analytical latency model, the hop latency obtained by Cooja is correlated to the calculation of the delay involved in the hop. Herein, the hop latency of 5 vehicles connected to a router is 1 second. This is less time compared to the communication latency obtained during the pre-election process. Also, the multi-hop network (single-hop to 4-hop) latency is evaluated. For the self-healing process, the latency occurred during the event response is impacted by the fitness computation process and post-election process. Herein, the number of the eligible nodes to compete and replace the departed node play an important factor in evaluating the latency during the fitness process. Also, the number of nodes that the new replacement node establishes connection with post-election impact the latency in the response and resuming the operation of the network. The

physical network based on Texas Instruments CC2538 is implemented for evaluating the impact of RSSI on the network mainly when a node starts to depart the network. Also, the testbed has provided an evaluation for the router capacity that is correlated to the virtual node capacity and the road capacity.

In summary, the research question presented in Chapter 1 was answered with the focus on problem definition and solution components, solution modelling and analysis, and model validity. These components were presented mainly in Chapter 4, 5, and 6.

7.3 Future Directions

The contribution accomplished in this thesis requires some future work to be identified for enhancing the overall concept. From the road traffic model point of view, the highway has been utilized as the main scenario for the modelling and testing the given ideology. This approach needs to be tested with other road scenarios such as the city roads as it can provide different capacity and density that can impact the distribution and performance of VN. From the vehicular grouping approach point of view, it would be useful to explore artificial intelligence (AI) models for the future prediction of the vehicular route to enhance the strategy of the event response before the occurrence of the event. The latency was one of main performance measures focused on in this thesis for analysing the system. Slow reaction to the dynamic events in the network causes latency in data flow and requires efficient operation for reducing latency. Such network demands high degree of flexibility with effective real time computational capabilities and autonomous self-structure mechanism. This is highlighted with utilization of the virtualization and SDN technologies that provided to some extent the required latency analysis before the actual physical implementation. To further realize this vision, it is anticipated that the sixth generation (6G) communication system is heading towards fulfilling zero latency requirements. The performance of 6G would enable closed-loop autonomous networks supported by artificial intelligence (AI), highly dynamic, extremely heterogeneous. Hence, this is worth to explore in the future.

As the work adopts a cloud-based solution, it would be worth exploring whether some of the vehicular computation and data processing could be done locally at the edge of the network rather than sending the information to the cloud servers. The group head

and each group member could be able to handle some of the computation formulating the edge layer. Also, the RSU or UAV could participate in data processing and storage formulating the stationary or mobile fog layer. Integrating the Edge-Fog concept into the nodes within the network can facilitate the network flexibility where some nodes could have the ability in handling some of the services and assisting the formulation of the network.

Appendix

A.1 A Sample of C Code for Channel Access Method

For TDMA:

```
PROCESS_THREAD(cc2538_demo_process, ev, data)

{

    PROCESS_EXITHANDLER(broadcast_close(&bc))

    PROCESS_BEGIN();

    counter = 0;

    broadcast_open(&bc, BROADCAST_CHANNEL, &bc_rx);

    while(1) {

        etimer_set(&et, CLOCK_SECOND*1);

        PROCESS_YIELD();

        //if(Transmit_Flag==0) //For (CSMA) mode: The status of the flag is not checked
```

```

{

    packetbuf_copyfrom(&c, sizeof(c)); //c is the array of sensed data and node ID
to be transmitted

    broadcast_send(&bc);

}

}

}

```

For CSMA, the following changes are applied in the code:

```

PROCESS_THREAD(cc2538_demo_process, ev, data)

{

    PROCESS_EXITHANDLER(broadcast_close(&bc))

    PROCESS_BEGIN();

    counter = 0;

    broadcast_open(&bc, BROADCAST_CHANNEL, &bc_rx);

    while(1) {

```

```

etimer_set(&et, CLOCK_SECOND*1);

PROCESS_YIELD();

//if(Transmit_Flag==0) //For (CSMA) mode: The status of the flag is not checked
{

    packetbuf_copyfrom(&c, sizeof(c)); //c is the array of sensed data and node ID
to be transmitted

    broadcast_send(&bc);

}

}

}

```

A.2 The Sample Code for Data Transmission, Data Computation and Fitness Model Components

```

/*-----*/

static const struct broadcast_callbacks bc_rx = { broadcast_recv };

static struct broadcast_conn bc;

/*-----*/

void

rt_callback(struct rtimer *t, void *ptr)

```

```
{  
  
    leds_off(LED_PERIODIC);  
  
}  
  
/*-----*/  
  
PROCESS_THREAD(cc2538_demo_process, ev, data)  
  
{  
  
    PROCESS_EXITHANDLER(broadcast_close(&bc))  
  
    PROCESS_BEGIN();  
  
    counter = 0;  
  
    count_flag=0;  
  
    broadcast_open(&bc, BROADCAST_CHANNEL, &bc_rx);  
  
    while(1) {  
  
        if(count_flag==0)  
  
        {  
  
            etimer_set(&et, CLOCK_SECOND);  
  
            count_flag=1;           //A flag variable is usually given two values 0 and 1
```

```
}

```

```
PROCESS_YIELD();

```

```

/*****
*****

```

```

/*****RSSI of R1-R2 *****/

```

```
transmit_of_rssi_wrt_R2_dbl = rand();

```

```
transmit_of_rssi_wrt_R2_intpart = (int)transmit_of_rssi_wrt_R2_dbl;

```

```
transmit_of_rssi_wrt_R2_intpart = abs(transmit_of_rssi_wrt_R2_intpart);

```

```
transmit_of_rssi_wrt_R2_intpart = (transmit_of_rssi_wrt_R2_intpart%73); //max of
RSSI depends on a defined range (0_-98) as this is the bounded range

```

```
transmit_of_rssi_wrt_R2_intpart=transmit_of_rssi_wrt_R2_intpart_value+transmit_of
_rssi_wrt_R2_intpart;

```

```
transmit_of_rssi_wrt_R2_intpart = (-1)*(transmit_of_rssi_wrt_R2_intpart);

```

```

/*****
*****

```

```

/*****RSSI of R1-R3 *****/

```

```
transmit_of_rssi_wrt_R3_dbl = rand();

```

```
transmit_of_rssi_wrt_R3_intpart = (int)transmit_of_rssi_wrt_R3_dbl;

```

```

transmit_of_rssi_wrt_R3_intpart = abs(transmit_of_rssi_wrt_R3_intpart);

transmit_of_rssi_wrt_R3_intpart = (transmit_of_rssi_wrt_R3_intpart%43); //max of
RSSI depends on a defined range (0_98) as this is the bounded range

transmit_of_rssi_wrt_R3_intpart=transmit_of_rssi_wrt_R3_intpart_value+transmit_of
_rssi_wrt_R3_intpart;

transmit_of_rssi_wrt_R3_intpart = (-1)*(transmit_of_rssi_wrt_R3_intpart);

/*****
*****/

/*****RSSI of R1-R4 *****/

transmit_of_rssi_wrt_R4_dbl = rand();

transmit_of_rssi_wrt_R4_intpart = (int)transmit_of_rssi_wrt_R4_dbl;

transmit_of_rssi_wrt_R4_intpart = abs(transmit_of_rssi_wrt_R4_intpart);

transmit_of_rssi_wrt_R4_intpart = (transmit_of_rssi_wrt_R4_intpart%20); //max of
RSSI depends on a defined range (0_98) as this is the bounded range

transmit_of_rssi_wrt_R4_intpart=transmit_of_rssi_wrt_R4_intpart_value+transmit_of
_rssi_wrt_R4_intpart;

transmit_of_rssi_wrt_R4_intpart = (-1)*(transmit_of_rssi_wrt_R4_intpart);

/*****
*****/

/*****Instantaneous speed of R1*****/

transmit_of_speed_R1_dbl = rand();

```

```

transmit_of_speed_R1_intpart = (int)transmit_of_speed_R1_dbl;

transmit_of_speed_R1_intpart = abs(transmit_of_speed_R1_intpart);

transmit_of_speed_R1_intpart = (transmit_of_speed_R1_intpart%35);      /*Setting
the maximum possible value of speed to say,120 Km/hr*/

transmit_of_speed_value_R1          =      transmit_of_speed_R1      +
transmit_of_speed_R1_intpart;

/*****
*****
*****/

/*RSSI Mean*/

/*****
*****
*****/

short signed Sum_RSSI_R2=0;

short signed Sum_RSSI_R3=0;

short signed Sum_RSSI_R4=0;

for ( x=0; x<3; x++)

{

    RSSI_R2[x]=transmit_of_rssi_wrt_R2_intpart;

    RSSI_R3[x]=transmit_of_rssi_wrt_R3_intpart;

```

```
RSSI_R4[x]=transmit_of_rssi_wrt_R4_intpart;
```

```
Sum_RSSI_R2 = Sum_RSSI_R2 +RSSI_R2[x];
```

```
Sum_RSSI_R3 = Sum_RSSI_R3 +RSSI_R3[x];
```

```
Sum_RSSI_R4 = Sum_RSSI_R4 +RSSI_R4[x];
```

```
}
```

```
Avg_RSSI_R2= Sum_RSSI_R2/3;
```

```
Avg_RSSI_R3= Sum_RSSI_R3/3;
```

```
Avg_RSSI_R4= Sum_RSSI_R4/3;
```

```
Mean_All_RSSI = (Avg_RSSI_R2 + Avg_RSSI_R3 + Avg_RSSI_R4 )/3;
```

```
//printf("average: %d,%d,%d.\n", Avg_RSSI_R2, Avg_RSSI_R3, Avg_RSSI_R4);
```

```
//printf("mean RSSI: %d.\n", Mean_All_RSSI);
```

```

/*****
*****
*****/

```

```
/*Speed Mean*/
```

```
/******  
*****  
*****/  
  
short signed Sum_Speed_R1=0;  
  
short signed Sum_Speed_R2=0;  
  
short signed Sum_Speed_R3=0;  
  
short signed Sum_Speed_R4=0;  
  
for ( x=0; x<4; x++)  
{  
  
    Speed_R1[x]=transmit_of_speed_value_R1;  
  
    Speed_R2[x]=transmit_of_speed_value_R2;  
  
        Speed_R3[x]=transmit_of_speed_value_R3;  
  
        Speed_R4[x]=transmit_of_speed_value_R4;  
  
    Sum_Speed_R1 = Sum_Speed_R1 +Speed_R1[x];  
  
        Sum_Speed_R2 = Sum_Speed_R2 +Speed_R2[x];  
  
        Sum_Speed_R3 = Sum_Speed_R3 +Speed_R3[x];  
  
        Sum_Speed_R4 = Sum_Speed_R4 +Speed_R4[x];  

```

```

}

Avg_Speed_R1= Sum_Speed_R1/4;

Avg_Speed_R2= Sum_Speed_R2/4;

Avg_Speed_R3= Sum_Speed_R3/4;

Avg_Speed_R4= Sum_Speed_R4/4;

Mean_All_Speed = (Avg_Speed_R1 + Avg_Speed_R2 + Avg_Speed_R3 +
Avg_Speed_R4)/4;

// printf("mean_speed: %d.\n", Mean_All_Speed);

/*****
*****
*****/

/*Calculation of Speed Variance*/

/*****
*****
*****/

Speed_Variance= (Mean_All_Speed - transmit_of_speed_value_R1);

//printf("Speed Variance for R1: %d.\n", Speed_Variance);

```

```

/*****
*****
*****/

/*Fitness model computation*/

/*****
*****
*****/

fiddle_factor_Avg_RSSI= (100/Avg_RSSI_max_range);

fiddle_factor_Speed_Variance= (100/Speed_Variance_max_range);

weight_Avg_RSSI= (100-(((fiddle_factor_Avg_RSSI)*(Mean_All_RSSI))));

weight_Speed_Variance=(100-((fiddle_factor_Speed_Variance*Speed_Variance)));

normalized_weight_FCH=(weight_Avg_RSSI+weight_Speed_Variance);

printf("fiddle factor Avg RSSI of R1: %0.2f \t ", fiddle_factor_Avg_RSSI);

printf("fiddle factor Speed Variance R1: %0.2f \t", fiddle_factor_Speed_Variance);

printf("weight Avg RSSI of R1:%d \t", weight_Avg_RSSI);

printf("weight Speed Variance of R1:%d \t", weight_Speed_Variance);

printf("Normalized weight of R1 : %0.3f \t", normalized_weight_FCH);

```

```

//printf("Normalized weight of R1: %d.\n", normalized_weight_FCH);

/*****
*****
*****/

R1_own_sensed_values_print_counter++;

if((R1_own_sensed_values_print_counter%1)==0){

    printf("Vehicular R1 node with Node ID %d is broadcasting the following sensed
values i.e. '(1) M-Hello_Candidate':\n", node_ID);

    printf("RSSI of vehicular R1 with Node ID %d with respect to R2           :%d
dBm.\n", node_ID, transmit_of_rssi_wrt_R2_intpart);

    printf("RSSI of vehicular R1 with Node ID %d with respect to R3           :%d
dBm.\n", node_ID, transmit_of_rssi_wrt_R3_intpart); //%d is the format specifier for
printing integer values. One d means printing one value

    printf("RSSI of vehicular R1 with Node ID %d with respect to R4           :%d
dBm.\n", node_ID, transmit_of_rssi_wrt_R4_intpart);

    printf("Instantaneous speed of vehicular R1 with Node ID %d             :%d
Km/hr.\n", node_ID, transmit_of_speed_value_R1);

    printf("mean RSSI of vehicular R1 with Node ID %d                       :%d
Km/hr.\n", node_ID, Mean_All_RSSI);

    printf("mean_speed of vehicular R1 with Node ID %d                     :%d
Km/hr.\n", node_ID, Mean_All_Speed);

    printf("speed variance of vehicular R1 with Node ID %d                 :%d
Km/hr.\n", node_ID, Speed_Variance);

```

```

// printf("Instantaneous speed of vehicular R2 with Node ID %d           :%d
Km/hr.\n", node_ID, transmit_of_speed_value_R2);

```

```

// printf("Instantaneous speed of vehicular R3 with Node ID %d           :%d
Km/hr.\n", node_ID, transmit_of_speed_value_R3);

```

```

// printf("Instantaneous speed of vehicular R4 with Node ID %d           :%d
Km/hr.\n", node_ID, transmit_of_speed_value_R4);

```

```

for (x=1;x<=MAX_NODES;x++)

```

```

{

```

```

if(recv_speed_value_of_R2[x]>0){

```

```

child_count++;

```

```

//printf("Node IDs of the immediate children connections of vehicular router node
with Node ID %d :", node_ID);

```

```

//printf("%d|", x);

```

```

}

```

```

}

```

```

// printf("Number of immediate children connections of vehicular router node with
Node ID %d :%d children.\n", node_ID,child_count);

```

```

// printf("Node IDs of the immediate children connections of vehicular router node
with Node ID %d are as follows:\n", node_ID);

```

```

for (x=1;x<=MAX_NODES;x++) //the "x" is called a loop counter. it is initialized to 1.

```

```

//the test expression x<=MAX_NODES is evaluated

```

```

{

if(recv_speed_value_of_R2[x]>0){

//child_count++;

    //printf("Node IDs of the immediate children connections of vehicular router node
with Node ID %d :", node_ID);

    printf("|%d|", x);

}

}

//printf("\n-----\n");
-----\n");

printf("\n");

actual_child_count_to_be_broadcasted=child_count;

child_count=0;

}

if(ev == PROCESS_EVENT_TIMER) {

    leds_on(LED_PERIODIC);

counter++;

essential_polling_array_elements_plus_R1_broadcasting_own_info[0]=node_ID;

```

```
essential_polling_array_elements_plus_R1_broadcasting_own_info[1]=TIME_IN_SEC -  
45;
```

```
    essential_polling_array_elements_plus_R1_broadcasting_own_info[2]=1;
```

```
essential_polling_array_elements_plus_R1_broadcasting_own_info[3]=transmit_of_rs  
si_wrt_R2_intpart;
```

```
essential_polling_array_elements_plus_R1_broadcasting_own_info[4]=transmit_of_rs  
si_wrt_R3_intpart;
```

```
essential_polling_array_elements_plus_R1_broadcasting_own_info[5]=transmit_of_rs  
si_wrt_R4_intpart;
```

```
essential_polling_array_elements_plus_R1_broadcasting_own_info[6]=transmit_of_sp  
eed_value_R1;
```

```
    //
```

```
essential_polling_array_elements_plus_R1_broadcasting_own_info[7]=transmit_of_sp  
eed_value_R2;
```

```
    //
```

```
essential_polling_array_elements_plus_R1_broadcasting_own_info[8]=transmit_of_sp  
eed_value_R3;
```

```
    //
```

```
essential_polling_array_elements_plus_R1_broadcasting_own_info[9]=transmit_of_sp  
eed_value_R4;
```

```
    essential_polling_array_elements_plus_R1_broadcasting_own_info[7]=  
Mean_All_Speed;
```

```

    essential_polling_array_elements_plus_R1_broadcasting_own_info[8]=
Speed_Variance;

    essential_polling_array_elements_plus_R1_broadcasting_own_info[9]=
Mean_All_RSSI;

essential_polling_array_elements_plus_R1_broadcasting_own_info[10]=actual_child_
count_to_be_broadcasted;

    //
essential_polling_array_elements_plus_R1_broadcasting_own_info[8]=Acknowledgme
nt_to_other_router_nodes_with_avg_info;

/*****
*****
*****/

/*Time interval for polling can be changed here*/

    etimer_set(&et, CLOCK_SECOND*3);

/*****
*****
*****/

/*****
*****
*****/

    /*Packets are transmitted (broadcasted) using this function*/

    packetbuf_copyfrom(&
essential_polling_array_elements_plus_R1_broadcasting_own_info,          sizeof(
essential_polling_array_elements_plus_R1_broadcasting_own_info));

```

```

//however that function could look like
packetbuf_copyfrom(&counter, sizeof(counter))

broadcast_send(&bc);

/*****
*****
*****/

if(counter==MAX_NODES)
{

counter=(counter % MAX_NODES);

printf("R1 is transmitting the message '(1) M-Hello_Candidate' to obtain RSSI
and speed of other router nodes.....\n");

printf("R1 is receiving the message '(1) M-Hello_Candidate' from other routers
(as shown below):\n");

printf("Node ID: received RSSI with respect to R2(dBm), received RSSI with
respect to R3(dBm), received RSSI with respect to R4(dBm), received speed of
R2(Km/hr), received speed of R3(Km/hr), received speed of R4(Km/hr)\n");

printf("R1 is transmitting the message '(2) M-Ack' with RSSI_Avg, Speed_Avg,
Speed_Variance to other router nodes.....\n");

printf("Node ID of the router nodes and its RSSI_Avg, Speed_Avg,
Speed_Variance (i.e. itself) (dBm)\n");

for (x=1;x<=MAX_NODES;x++) //x<=the number that is mentioned within the counter
{

```

```
//if(recv_speed_value_of_R2[x]>90){

printf("Node ID %d: %d,%d,%d,%d,%d,%d|", x, recev_rssi_wrt_R4_intpart[x],
recv_speed_value_of_R2[x], recv_speed_value_of_R3[x], recv_speed_value_of_R4[x],
recv_Mean_All_Speed_R2[x],recv_Speed_Variance_R2[x]);

//}

}

//}

//printf("\n-----\n");

printf("\n");

        etimer_set(&et, CLOCK_SECOND*TIME_IN_SEC);

        }

}

}

PROCESS_END();

}
```

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