A SUSTAINABLE INTERNET DATA DISSEMINATION ARCHITECTURE BY UTILIZING THE EXISTING PUBLIC TRANSPORT NETWORKS

A THESIS SUBMITTED TO AUCKLAND UNIVERSITY OF TECHNOLOGY
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Abstract

The traditional world has transformed into a digital society where almost anything can be accessed from anywhere. However, this digital society is responsible for the explosive growth of high-volume, high-velocity, and high-variety information assets, with high demand for “Big Data”. Not only this, most services in this digital world have become data-driven, thus generating big data that require sharing, storing, processing, and analysis, which ultimately overburden existing infrastructure-based networks, increase the energy demands exponentially, and leads to CO_2 carbon emissions, which could finally end up seriously harming the environment. Several challenges are being posed such as the accumulation process of these data from different areas of a smart city and alleviating bandwidth of infrastructure in an energy-efficient manner. Therefore, to tackle these challenges, we proposed Public Transport Assisted Data Dissemination System (PTDD), where public buses enable a service as a data carrier in a smart city as an alternative communication channel and this opportunistic sensing comprises delay-tolerant data collection, processing, and disseminating from one place to another place around the city. The biggest motivation is that the public transport network is an existing infrastructure and can be utilised efficiently for energy-efficient data dissemination. The main contribution of the thesis is highlighted below:

Firstly, we identified all the characterizations of public transport including their movement pattern to analyze their great potential to form a data dissemination network.

Next, an advanced neural network (NN) algorithm was applied to locate the realistic arrival time of public buses for the data allocation. We used the Auckland transport (AT) buses data set from the transport agency to validate our model for the level of accuracy in predicted bus arrival time and scheduled arrival time to disseminate data using bus services.

Secondly, we defined a heterogeneous network architecture called Software-Defined Connectivity Architecture (SDCA) that utilizes the flow of transport network using buses to start the forwarding process from nearby parking/offloading spots to disseminate data along with conventional networks. The controller selects the optimal network using Multi-Attribute Decision Making with defining a utility function and Analytical Hierarchical Process (AHP) method for criteria weights to rank the network. Data were uploaded onto buses as per their dwelling time at each stop and terminals within the coverage area of deployed RSU. Based on the analytical, and numerical analysis, we understand that optimal networks can be selected as per different services and demands of the user.

Finally, we proposed an energy consumption model for energy-efficient data dissemination using PTDD. We used different optimisation techniques to minimize the energy cost to fulfil all demands of all bus stops. We used the SAS optimization tool and Cplex solver for finding out the best energy-efficient network. This work provides strong evidence that significant energy savings can be achieved while still guaranteeing data delivery in the heterogeneous network.

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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 nor material which to a substantial extent has been accepted for the qualification of any other degree or diploma of a university or other institution of higher learning.

Signature of candidate

Publications

Journal Publications

- **R. Munjal**, Liu, W. Liu, X. J. Li, J. Gutierrez, "A Neural Network-Based Sustainable Data Dissemination through Public Transportation for Smart Cities." Sustainability 12.24 (2020): 10327. https://doi.org/10.3390/su122410327 **Impact Factor: 3.275**

Book Chapters

- **R. Munjal**, W. Liu, X. J. Li, J. Gutierrez and M. Furdek," Sustainable Crowdsensing Data Dissemination using Public Vehicles", 2018, A. -S. K. Pathan (Ed.), Crowd Assisted Networking and Computing (pp. 77-110). CRC Press

Conference Publications

- **R. Munjal**, W. Liu, X. J. Li, and J. Gutierrez, "Big Data Offloading using Smart Public Vehicles with Software-Defined Connectivity," 2019 IEEE Intelligent Transportation Systems Conference (ITSC), Auckland, New Zealand, 2019, pp. 3361-3366, doi: 10.1109/ITSC.2019.8917322

- **R. Munjal**, W. Liu, X. J. Li, J. Gutierrez and M. Furdek, "Sustainable massive data dissemination by using software defined connectivity approach," 2017 27th International Telecommunication Networks and Applications Conference (ITNAC), Melbourne, VIC, 2017, pp. 1-6, doi: 10.1109/ATNAC.2017.8215404.

- **R. Munjal**, W. Liu, X. J. Li, J. Gutierrez, and P. H. J. Chong, "Telco asks transp: Can you give me a ride in the era of big data?," 2017 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), Atlanta, GA, 2017, pp. 766-771, doi: 10.1109/INFCOMW.2017.8116473.

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Chapter 1

Introduction

1.1 Introduction

With the emergence of new advancements over the past few years, several industry sectors have benefited from new technologies. The trend is that more and more technologies are created to fulfill our everyday demands. However, their efficient and effective use is another factor to consider. Moreover, while looking back at the past years, it is crystal clear that our daily lives are getting equipped with modern devices such as smartphones, smart TVs, and smartwatches. The third-generation (3G), fourth-generation (4G), and fifth-generation (5G) technologies are growing fast with many more advancements to fulfill user's streaming requirements and real-time data traffic distribution [1]. These rapid developments are making our life easier and smart. These advancements in technologies are giving us benefits but on the other hand, are equally responsible for energy consumption. However, many methods have been introduced such as traffic offloading to nearby neighboring nodes via low power direct connections. The recent advancements in networking and embedded computing technologies encouraged the introduction of Cyber-Physical Systems (CPS) which are capable of sensing and affecting their environment for improved convenience. CPS depends upon heterogeneous networks where all the physical entities and processes are interconnected and controlled by cyber-components. These networks must be able to support mobile wireless CPSs that are demanding new requirements related to architectural flexibility and heterogeneity without compromising the Quality of Service (QoS).

Vehicular networks [2] are visualized to satisfy the upcoming demands for improved transportation efficiency and potentially exert influence on others. Moreover, researchers have validated that vehicular networks can share sensory data among vehicles and infrastructure, thus remarkably improving the overall sensing performance. In addition to it, researchers attempt to mitigate the traffic flow burden by finding out alternative data transmission network architecture. Several data offloading techniques have been introduced using cellular base stations, WI-FI hotspots, and vehicular networks, respectively. Not only this, many researchers initiated aiming at the Internet of Vehicles (IoV), where smart vehicles get equipped with computing and storage capabilities to communicate with surrounding infrastructure.

To address the challenge of energy efficiency, we are proposing a subcategory of IoV as the Internet of Buses (IoB), where public buses enable a service of the data carrier. We will come up with a new approach by utilizing the existing public transport network and offload the data from the wired/wireless network to the scheduled public transport vehicles. The public transport vehicles are the moving agents in this new communication paradigm, and they enable an alternative communications option in addition to the current infrastructure-based communications to lessen the energy consumption and carbon footprint. With the constantly increasing energy consumption in transmissions of explosive growing data, the more energy-efficient and sustainable solutions are necessary to be incorporated into the future wired and wireless networks.

1.2 Motivation

The advancements of Information and Communications Technologies (ICT) have contributed to an explosive growth of big data. The infrastructure-based networks are becoming increasingly overloaded, while the cost of maintaining and expanding the infrastructure to accommodate the Big Data communications remains high. Also, the use of these networks keeps increasing energy demand and consumption. As a result, energy consumption is one of the concerning issue. These matters are named as “green networking”, relate to energy-efficient architecture and product layout, device usage, and the network protocols.

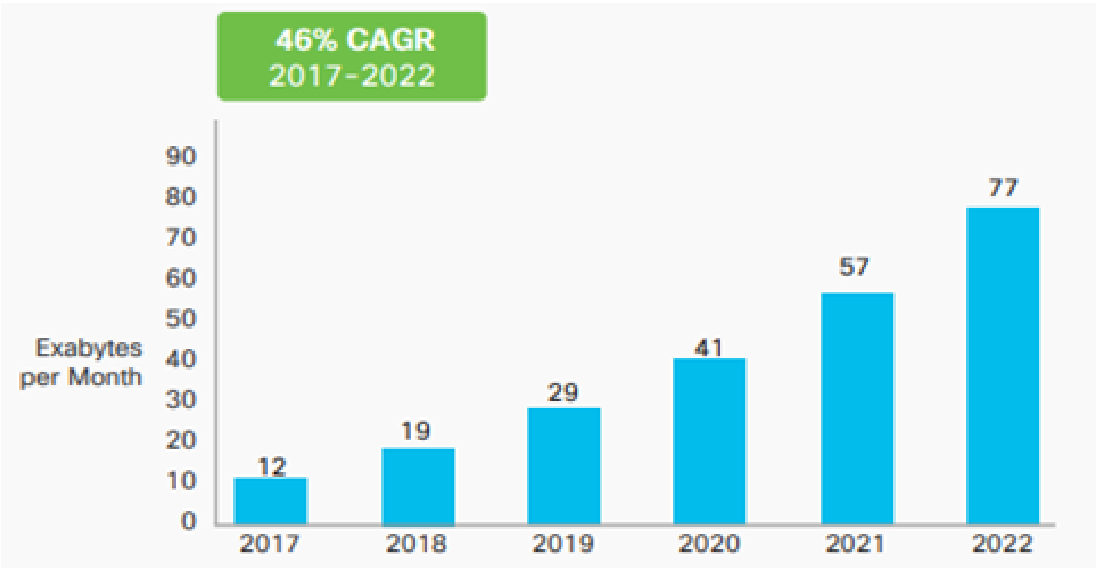

Figure 1.1: Cisco Forecasts of Mobile Data Traffic Exabytes /Month by 2022

To address the challenge of energy efficiency, we develop a new approach by utilizing the existing public transport network and offload the data from the wired/wireless network to the scheduled public transport vehicles. The public transport vehicles are the moving agents in this new communication paradigm, and they enable an alternative communications option in addition to the current infrastructure-based communications to reduce the energy consumption and carbon footprint. Fig. 1.1 is Cisco’s forecast [3] in 2017 for the mobile traffic Exabyte per month till 2022, which shows that data traffic is almost triple in these next 5 years.

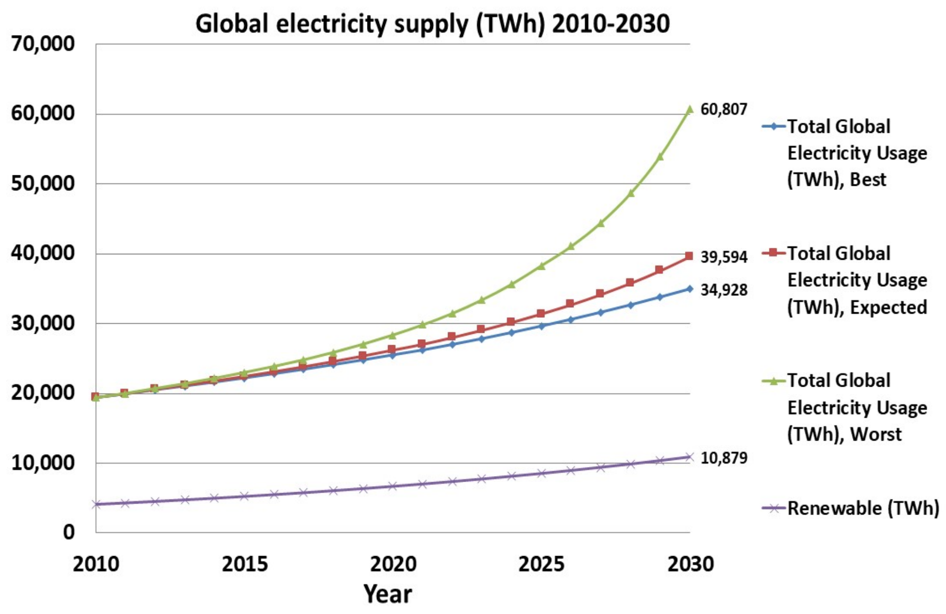

Figure 1.2: Global Electricity Supply 2010–2030

The global electricity supply by all equipment is defined in Fig. 1.2 and Fig. 1.3 [4] with the best, expected, and worst-case scenarios of compund annual growth rate (CAGR). The electricity command of communication technology will reach up to 30,715 TWh of a worst-case scenario in 2030.

In addition to it, big data has become the most attractive topic nowadays in both the academic and corporate worlds. Data has been generated from many sources such as scientific research (physics, astronomy, computational biology), Internet of Things (IoT), agricultural sensors, healthcare applications, social networking website (Linkedin, Twitter, Facebook. etc). Previously, big data has been defined with three different attributes [5]: volume, variety, and velocity. Now, two more features have been added: value and veracity, which is more about the quality of data and its value.

Nowadays, many applications consume a lot of Internet bandwidth to send massive

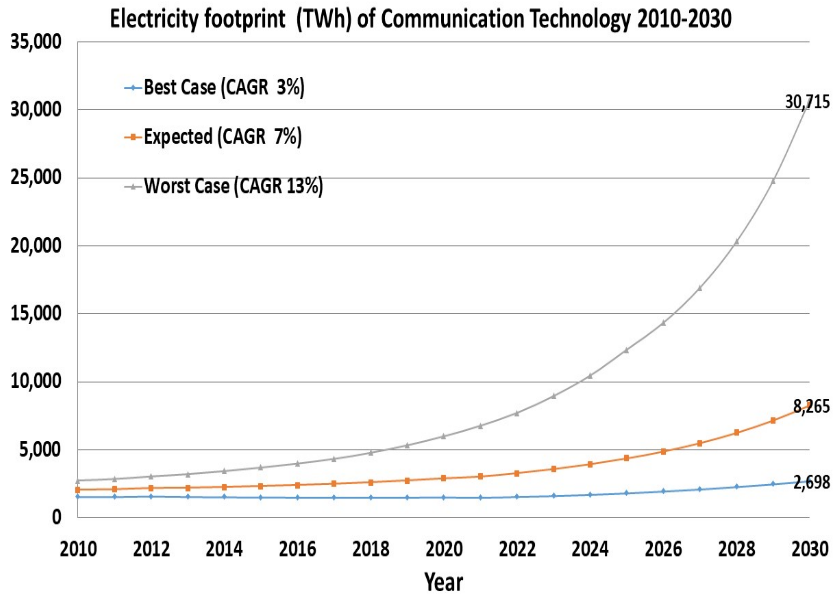

Figure 1.3: Global electricity Demand of Communication Technology 2010–2030

data over wide-area networks. Many big organizations transfer big data to keep backups of their everyday data, to synchronize search indexes between data centers, or to provide high-definition surveillance video records by government and audio/video sharing over social websites. Fig. 1.4 presented a detailed list of big data source generators that are demanding more bandwidth for transferring it from one place to another. Therefore, these big data applications' survivals would not be possible without the underlying support of networking due to their extremely large volume and computing complexity [6] data. Therefore, these big data applications' survivals would not be possible without the underlying support of networking due to their extremely large volume and computing complexity. This biggest challenge encourages the search for more connectivity options. Moreover, Fig. 1.5 shows the three digital laws: Kryder's law, Moore law, and Neilson's law [7] which states that new products come into the market with each passing year with new technology. The basic idea of Kryder's law is to double the storage capacity every 12 months. Moore's law is somewhat like Kryder but works on the processing speed of

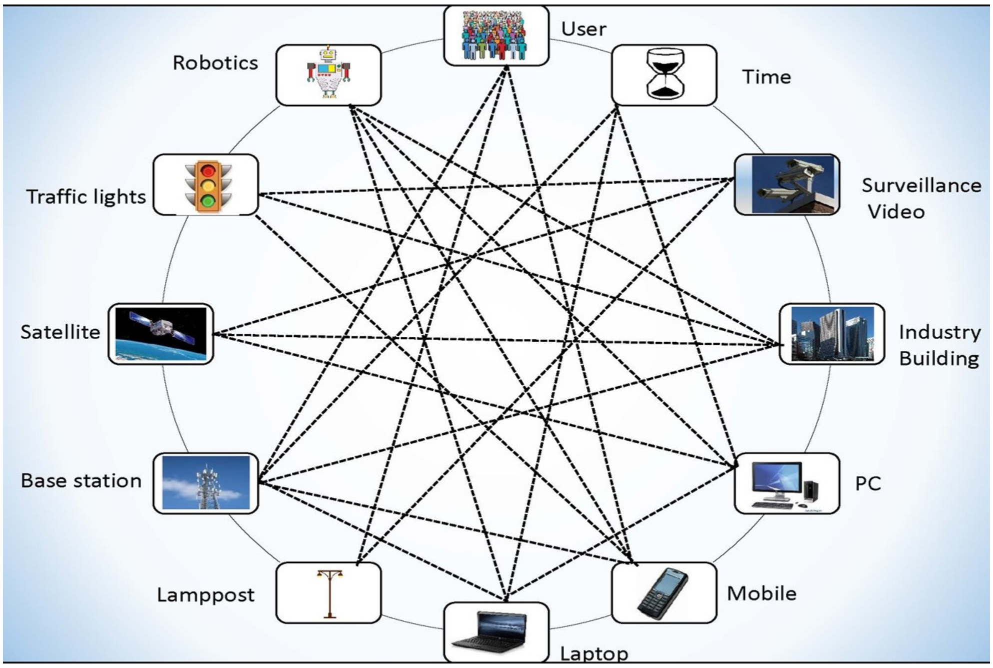

Figure 1.4: Big Data Source Generator

chips, which get doubled every 18 months. Moving forward to Neilson's law, which estimates that bandwidth doubles every twenty-one months, so this last component of digital experience lags both storage and processing speed.

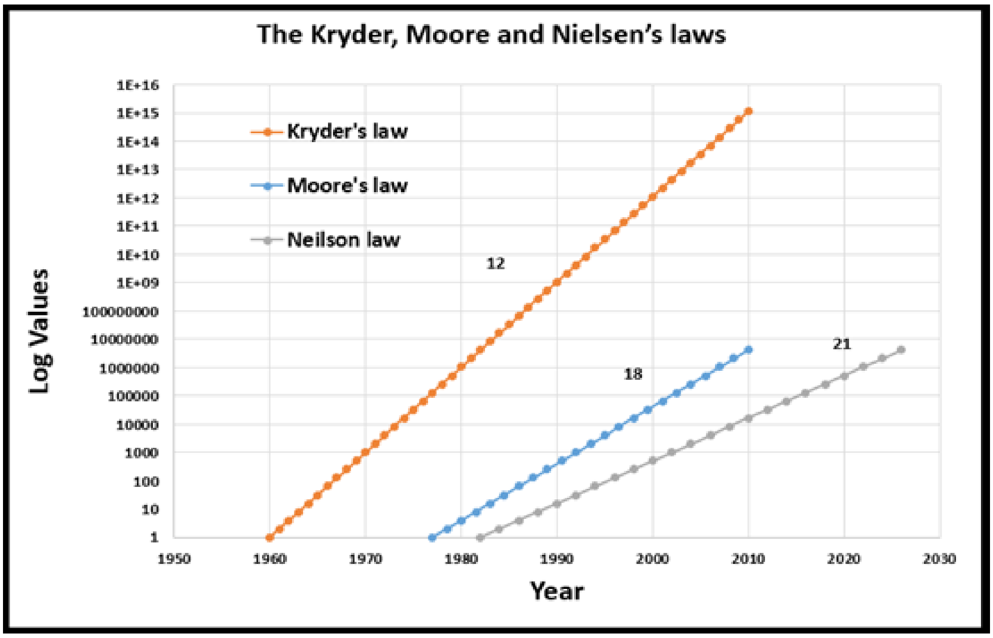

Figure 1.5: The Kryder, Moore and Nielsen's laws

These three laws clearly explain that whatever new network technology comes into the market, the available data (in online storage) is never being fully accessed by the new network technology and the end-users. There will always be a gap between the available bandwidth and the available data/information storage online. This big data need will never be satisfied with internet technology. Whenever there is a conflict between modern technology and users' desires, human desires always win so will keep advancing Internet technology. This non-stopping data need leads to more and more energy consumption, thus the carbon emission and finally harm the environment worse and worse. Therefore, we want to introduce a new option of utilizing the existing public transport networks to address this problem. Our solution can pave a possible way-out through decoupling the energy consumption from the data size and its transmission distance, sometimes might need to sacrifice the delay of data delivery.

Several attempts [8–10] in developing efficient, sustainable, and integrated (wired/wireless) networks have been made. The opportunistic network is one of the techniques to overcome this problem while disseminating data in store and the forward manner by connecting mobile devices. The key idea of the Opportunistic Network is that the mobility of nodes may help to deliver messages, whether it is connected or disconnected asynchronously in time [11]. Moreover, The Internet of Things (IoT) endures inflating from traditional homogeneous technologies with low resources to increasingly heterogeneous and resource-rich technologies.

1.3 Research Questions

The objective of this thesis is to design an energy-efficient data dissemination architecture in heterogeneous networks while utilizing public transport networks. It focuses on the sustainability of the network for energy-efficient communication. The key idea in this thesis is to best utilize the existing public transport networks and their scheduled movement of vehicles in proximity, to transmit and deliver the traffic with delay-tolerant features. It complements the traditional wired and wireless infrastructure-based data transmission, by offloading those traffics with delay-tolerant characteristics to the moving public transport vehicles with scheduled timetables such as bus, train, ferry, and plane for the data delivery in a heterogeneous network. The heterogeneous network deployments are a promising solution to improve the quality of services (QoS) and increase spectral efficiency with the low operational expense (OPEX) and energy consumption. The QoS can be more generalized defined in terms of data delivery and average delay.

Main Question: How to design a more sustainable Internet data dissemination architecture to accommodate big data demands in heterogeneous networks by utilizing the existing public transport networks?

The proposed research focuses on data dissemination techniques while offloading data from infrastructure to scheduled vehicles to obtain better communication with less consumption of energy in a heterogeneous network. The literature survey concludes that all people have been using the traditional way of communication for a long and even do not think about how they are switching from one layer to another layer. Our work will introduce a new layer of the scheduled vehicle to carry data without consuming extra energy from one place to another place. The scheduled vehicles have their predefined routes and prescheduled timings for a particular journey. The multilayer network framework can model the above problems and take optimal routing decisions across the different network layers include wired, wireless, and public transport networks. Each city has public transport available to make communication easier. It can be buses/shuttles/ferries to work as a data carrier. We have further subcategorized our research question:

RQ1 **What are the great potentials to utilize public transport network and their**

scheduled movements to accommodate big data demands for smart city applications?

To design an energy-efficient data dissemination architecture utilizing the existing public transport network, it is important to analyze the great potential or capacity of the public transport network to utilize them efficiently for data carrying. Moreover, this public transport network helps to carry only delay-tolerant data and how much potential does it have. In addition to it, how the delay-tolerant indicator (DTI) will impact the capacity of the public transport network. In addition to it, these public transport networks are being used due to their scheduled movement, there are many factors in real life which affect the arrival time of buses at each bus stop. Then, we have to analyze the bus arrival time is accurate to allocate data onto buses.

RQ2 **How to select optimal network as per different demands in heterogeneous network and allocate data onto that?**

For data dissemination in a heterogeneous network, how to identify which network is the optimal network as per the different demands of users. To make this optimal decision, who will be helping to decide for network selection and data forwarding using an optimal network. Some users have delay-tolerant requirements, but some users wish to send delay-sensitive data. Network selection decision depends upon many other attributes such as delay time, delivery probability, energy efficiency, and bandwidth of the different networks. There are other challenges as well such as data storage at bus stops in case of data allocation onto buses as per their stay time, entering time, and leaving time.

RQ3 **How much energy can be saved while transmitting data using public transport assisted data dissemination architecture in comparison with the traditional network?**

We will be designing an energy-efficient data dissemination architecture, but how much energy can be saved while using the public transport network. To address this issue, it is important to analyse the energy consumption in the case of traditional networks and vehicular networks to utilize them efficiently for data dissemination.

1.4 Contribution

The contribution of this thesis is to design energy-efficient data dissemination architecture in a heterogeneous network. Many researchers have devoted their efforts to improving the resource efficiency of ICT systems. Recently, there is fast-growing literature on energy efficiency and QoS, nevertheless, our work will focus on both perspectives simultaneously in a heterogeneous network. The proposed research emphasizes data dissemination techniques that will utilize existing public transport to make an energy-efficient network. Unfortunately, there is not much work to reveal the concept of energy efficiency in the heterogeneous network while offloading data from infrastructure towards scheduled vehicles. We have extensively reviewed the literature on green networking, delay-tolerant network, and heterogeneous network. A research gap has been identified, which is shown in Fig. 1.6.

Energy saving is the major concern along with the sustainability of quality in our findings. This finding has become the motivation for this thesis. Therefore, there are three main contributions as follows to cover the research gap.

Contribution 1: To design an energy-efficient data dissemination architecture in a heterogeneous network, first of all, it is important to know the great potential or capacity of the public transport network to consider as an alternative communication channel. We have proposed a new term Public Transport Assisted Data Dissemination System (PTDD). We will identify all the characterizations of the public transport bus system that

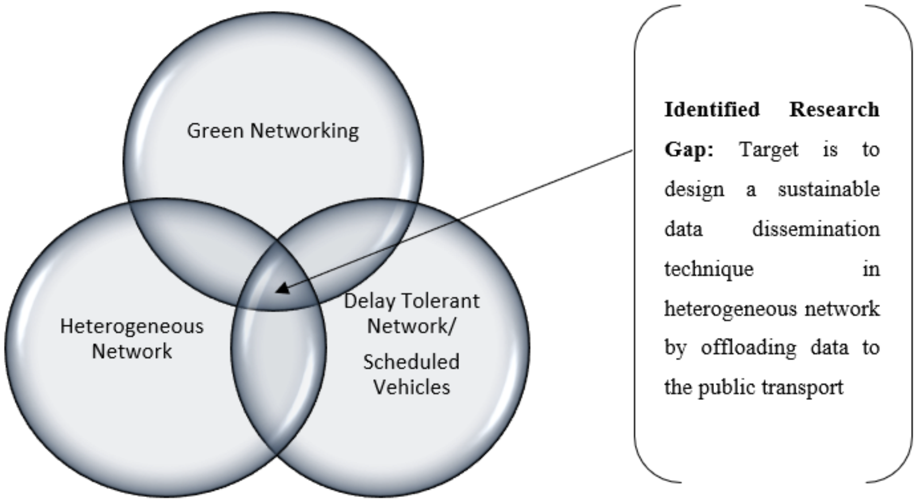

Figure 1.6: Research Gap Identified

currently exist and determine bus daily movement patterns to form a data transmission network. That will help us to know the capacity of the transport network. In addition to it, we are utilizing this public transport network due to their scheduled movement. However, the historical pattern of bus movement doesn't seem to be scheduled and need to analyze the accurate bus arrival time based upon their time and the route. We will apply the Advanced Neural Network algorithm to analyze the bus arrival time based upon the historical data. The obtained results will help to identify the difference between scheduled and predicted arrival time to estimate the accuracy to utilize public buses for data dissemination and will help to allocate data onto buses as per their stay time at the bus stop.

Contribution 2: We proposed a heterogeneous content delivery architecture to make an optimal network selection among different networks. We leverage this public transport and handle it using logical centralization with Software-Defined Connectivity Architecture (SDC) for efficient and better management of network selection among different networks. The SDC controller takes all the data forwarding decisions based upon different requirements of services. All these services have their pre-defined requirements and preferences based upon the urgency of data delivery or in other words, these services have important factors to decide among multiple attributes. The SDC controller uses Multi-Attribute Decision Making (MADM) for optimal network selection. The utility values are defined for all the criteria for the user's satisfaction. AHP method is being used for weighing attributes as per the preferences, which helps to rank the network-based upon priority vector. Furthermore, after selecting the public transport network, data gets allocated onto buses as per their stay time, entering time, and leaving time into the coverage of Roadside Unit (RSU) deployed at the bus stop.

Contribution 3: We have developed an energy model and delay model for traditional network and public transport network for energy-efficient data dissemination. We have used a multi-commodity flow problem for energy cost optimization to allocate data onto both networks for energy-efficiency. Next, we have applied capacitated vehicle routing problem for energy-efficient data dissemination. The result analysis validates that there is a significant amount of saving energy while using the public transport network.

1.5 Thesis Outline

The overall structure of the thesis comprises six chapters. The first chapter starts with an introduction to the relevant background, research motivation, idea, and research questions. Then, followed by a research gap identified with the comprehensive discussion of three frameworks: Green Networking, Delay Tolerant Network, and Heterogeneous network.

Chapter 2 review the detailed overview of these three frameworks discussed in Fig. 1.7. This chapter gives an overview of existing work done in the area of alternative communication channels and the other possible ways to disseminate data. We have explored the concept of using vehicles for communication with the concept of data

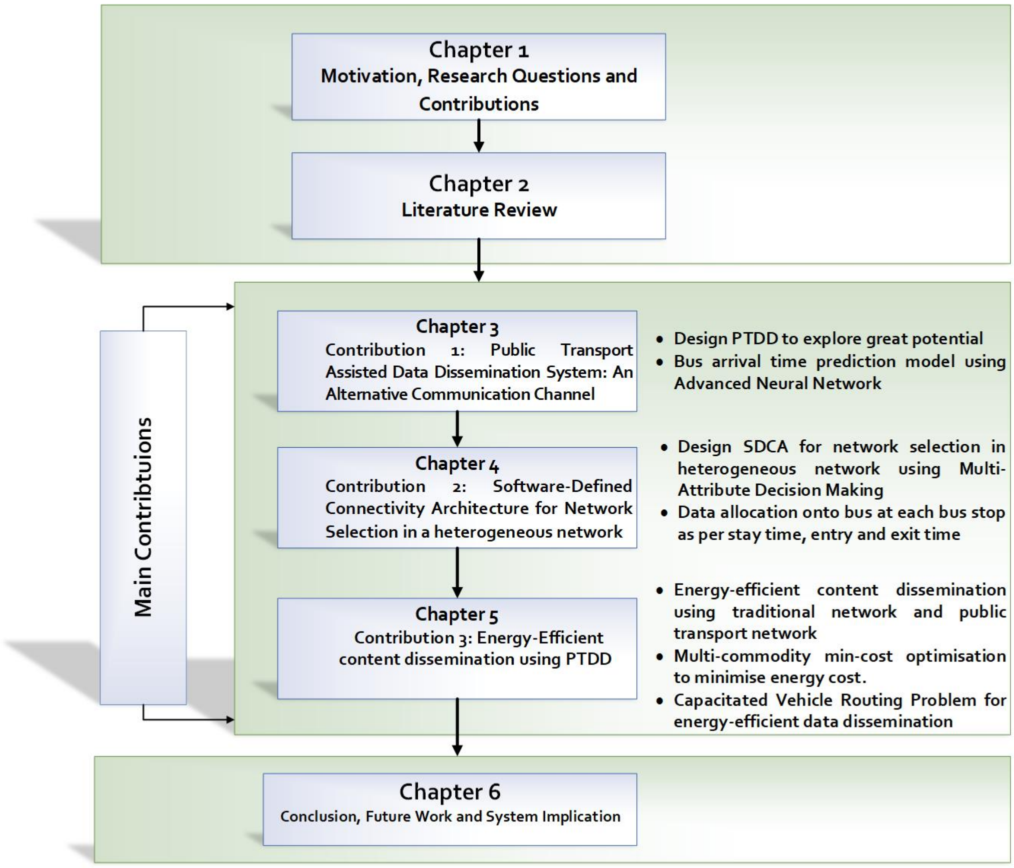

Figure 1.7: Thesis Structure

offloading which can be delayed or non-delayed offloading. This chapter also identifies the challenges and gaps that require bridges in the design of energy-efficient data dissemination architecture. Next, It also explains the methodology applied in this research. This chapter presents the details about the frameworks used for public transport assisted data dissemination architecture along with all the mathematical approaches to analyze the dataset and analytical models for validation of the models. In addition to it, the details about the procedures and processes used for conducting the study.

Chapter 3 illustrates the preliminary investigation of the research mainly focusing on the great potential behind using public transport networks to utilize them as an alternative communication channel for public transport assisted data delivery. The bus arrival time prediction model has been developed using the Advanced Neural Network (NN) algorithm for the accurate bus arrival time at each bus stop.

Chapter 4 illustrates the Software-Defined Connectivity (SDC) Architecture for network selection in a heterogeneous network. SDC is a paradigm with a central controller to leverage this public transport and handle it using logical centralization for efficient and better management of network selection among different networks. SDC controller uses the Multi-Attribute Decision Making (MADM) technique for network selection based upon different criteria and attributes. After selecting public transport as another network, the SDC controller evaluates the flow table and allocates data onto buses as per passing stops and stopping stops as per their predefined routes of sources and destination.

Chapter 5 draws upon the entire thesis, tying up all the analytical, theoretical, and empirical strands for energy-efficient content distribution. This chapter illustrates the energy model for the traditional network and public transport network. The energy consumption optimization model uses a network flow model to formulate a multi-commodity flow problem to find a more sustainable approach among traditional and public transport networks. We applied Capacitated Vehicle Routing Problem for energy-efficient data dissemination using selected buses.

Chapter 6 concludes all the contributions and the findings in this thesis. Also, the limitation of this research and future work are discussed in the end. Each of chapters three to five represents all contributions and answers to the research questions. The next section will highlight the research design and methodology adopted for our proposed research.

1.6 Research Design: Design of the Study

The main objective of our research is to design sustainable data dissemination architecture in a heterogeneous network. To achieve this objective, we have used the following methodology to solve our research questions. The proposed research follows the Design Science Research Methodology (DSRM) [12] research methodology to conduct the research. The most used frameworks of the process model are defined in Fig. 1.8 below. This methodology incorporates principles, practices, and procedures to carry out the research and meet the following three objectives. Firstly, it goes consistent with prior literature. Next is, it defines a minimal process model for performing our research. It provides mental modeling of research to present and evaluate.

The DSRM methodology includes six phases which are problem identification and motivation, define objectives of a solution, design and development, demonstration, evaluation, and communication. Each phase contains a set of activities undertaken to achieve specific goals. The entry point of the proposed research work is problem-centered initiation.

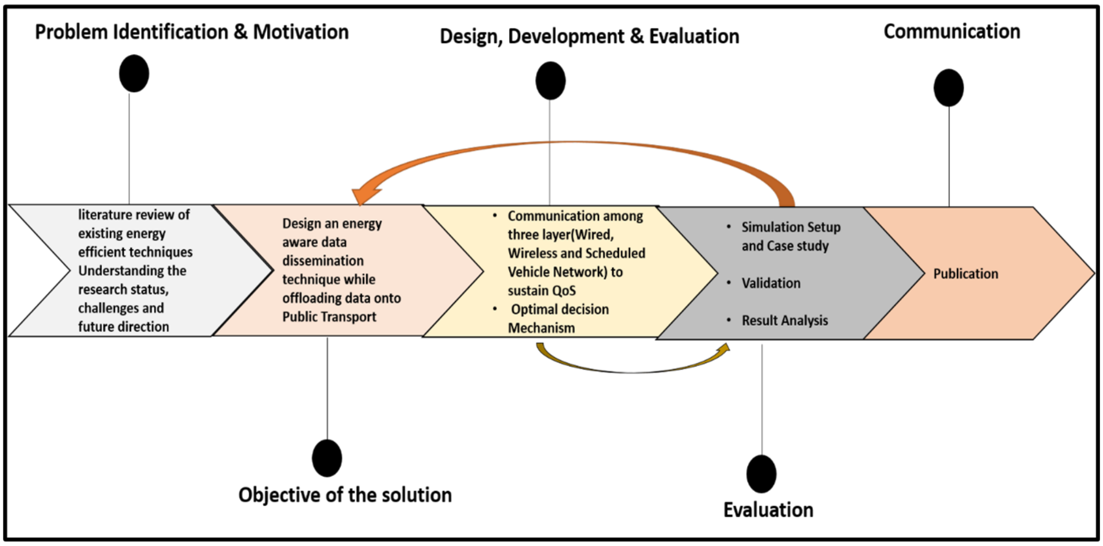

Figure 1.8: Design Science Research Methodology

1.6.1 Problem Identification and Motivation

This is the first phase, we performed a thorough literature review to identify the problem and findings of existing research scholars. This helps us to understand the research status, potential insights, challenges, and future directions. These findings further help us to understand the research theory, develop new ideas, guidance to develop a model, and construct an objective of the solution. Moreover, the foundation of our proposed the solution is the research gap identified from three main areas which are the green network, delay-tolerant network (DTN), and heterogeneous network. We have also identified problems that need to be addressed. One of the main concerns of the network industry is to minimize the energy consumption of network infrastructure by introducing many methods such as traffic offloading to nearby neighboring nodes via low power direct connections. Moreover, “Big Data” transfer is one of the biggest challenges faced by the Internet of Things (IoT). There is a long list of human activities, which generate large volumes of data, and these operations cannot be fulfilled by the available bandwidth. This finding has become the motivation to address our identified problem.

1.6.2 Objectives of a Solution

We have conducted a detailed literature review to assess the state of the art of research done in the past in case of offloading data to DTN in case of non-urgent traffic due to network congestion. Then figured out the challenges that this offloading scheme motivates us to work on energy-efficient networking techniques. We have further categorized the objectives of the solution in Section 1.3 to attempt our research questions. We will be designing an energy-efficient data dissemination architecture utilizing the public transport network. Therefore, we have used analytical modeling and a data-driven approach to aim for the solution to our research problem. While looking at the outlined objectives, we analyzed the public transport dataset to support our energy-efficient data dissemination architecture. We initiated with the finding of great potential behind using public transport network using Auckland public transport network data set. We proposed an analytical model in Chapter 3 to understand the scheduled movement of buses and the capacity of the transport network to be utilized efficiently for data dissemination. We aim to decide the optimal network in a heterogeneous network for different requirements of used and different kinds of services. We defined the optimization problem and solved it using the SAS optimization solver in the next chapter. This network selection directs back to our main motive of energy efficiency in the Chapter 5, we did some numerical analysis to prove that the public transport network is an energy-efficient network to disseminate data to various locations.

1.6.3 Design and Development

This phase is about framework design and system model development as shown in Fig. 1.9. The first stage is the framework design process, we have already identified gap from the three main areas as discussed in Section 1.4: i) Green Networking ii) Delay Tolerant Network iii) Heterogeneous network.

Framework designs consist of our main motive to design a new system architecture for data dissemination in a heterogeneous network. This design process includes requirement specification, preliminary analysis, system development strategies, and implementation. The requirement specification phase is an iterative process for providing input to our system and deciding all the parameters to be considered. Moreover, this phase guides the implementation phase with a new research hypothesis. The system design and development are a constant improvement process with new concepts. System model development is a footing of a new approach to finding an alternative communication channel along with the existing traditional network. For that, we have identified the great potential behind using public transport networks in Chapter 3. Based

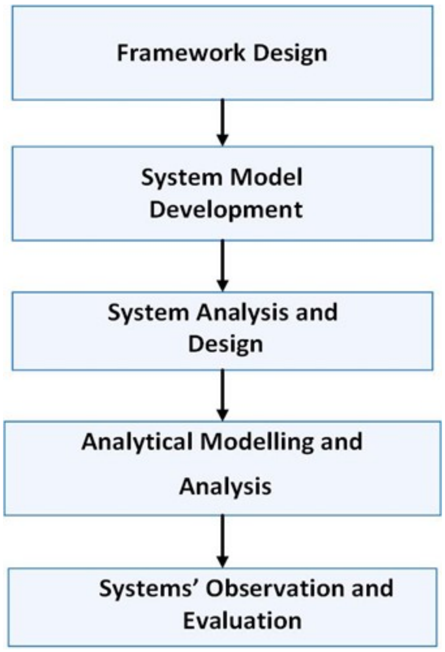

Figure 1.9: System Design and Development

on this theory, we further focused to design a sustainable data dissemination architecture. Many DTN routing protocols include human movement and vehicle mobility for data dissemination acting as a relay node with delay-tolerant features. However, we are taking into consideration vehicles as a data carrier, we did not aim to design a routing protocol. Our proposed research is mainly to design energy-efficient data dissemination architecture in the heterogeneous network. It was very challenging to find a convenient simulation tool for evaluation and validation. Therefore, to achieve our research objective, analytical modeling, simulation and data-driven approach using Machine learning have been used for evaluation and implementation.

1.6.4 Model Evaluation and Implementation

In this phase, we have been conducting several network simulations and sensitivity analysis with case scenarios in each chapter. It is being done to evaluate the effectiveness and efficiency of the proposed research. This simulation experiment provides us a means to measure and assess the effectiveness of our proposed approaches. The computer simulation is an old traditional way to evaluate and validate your model and researchers are using it the same way for ages. However, in our work, we have adopted the research methodology approach as shown in Fig. 1.10. We aim to design an energy-efficient data dissemination architecture in a heterogeneous network by a public transport network. Firstly, we explored the great potential behind using public transport networks, capacity analysis, and arrival time prediction modeling to have realistic information on bus arrival for data allocation in Chapter 3. Next, we described Software-Defined Connectivity Architecture to leverage the advantage of logical centralization to offload data onto vehicles. The controller will make forwarding decisions for network selection as per different services and user's requirements using Multi-Attribute Decision Making in Chapter 4. Finally, we explored an energy-efficient data dissemination scheme using PTDD in Chapter 5. These three contributions ultimately lead to a sustainable data dissemination architecture in a heterogeneous network. Public transport will be used as a data carrier to carry data all along with the city. These buses can accumulate data from data centers such as video surveillance, traffic monitoring, weather forecasting, and disaster scenarios, etc. Public transport is an existing infrastructure and can be utilized efficiently with energy cost savings.

Moving further, for evaluation and validation of our proposed research model, It is extremely expensive to design a real testbed for real-time validation. Therefore, we have adopted mathematical modeling, computer analysis, and statistical analysis using different platforms. Our research is a data-driven approach; We have used the Auckland Transport dataset in our case study for validation of our models. For our PTDD design framework, we chose Monte Carlo Simulations using MATLAB to evaluate the performance of mathematical concepts of the designed algorithm for each chapter. Monte Carlo Simulation is a well-known strategy in Computer Sciences to compute algorithms that rely on random sampling to obtain numerical results. Extensive analysis

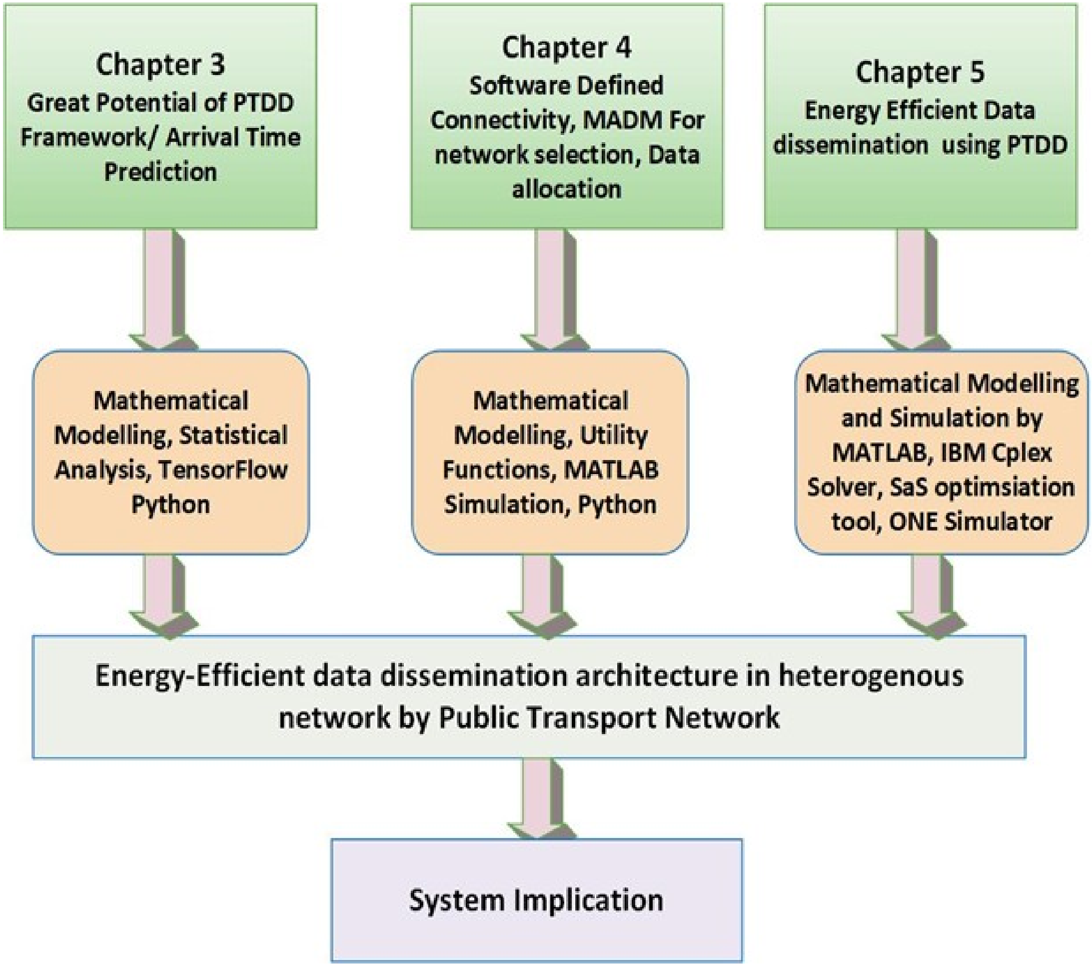

Figure 1.10: Block Diagram for the Adopted Methodology

is performed to calculate the capacity of the public transport network. In addition to it, for arrival time prediction modeling, we used TensorFlow Python to evaluate the prediction results of bus arrival time at each bus stop. These results give realistic information about buses' arrival time to allocate data onto them.

Moreover, we have used the AHP method for network selection among different networks. We have defined utility functions for user's preferences based upon different criteria. We used MATLAB for consistency check and to obtain weights for different attributes to rank different networks. Next, all buses are equipped with an On-Board unit and we have deployed RSU at each bus stop. The data will be allocated onto each bus when it encounters deployed RSU. We have tested the signal-to-noise ratio for different path loss exponent factors for data allocation and calculated offloading efficiency at each bus stop in Python.

Finally, for energy cost optimization, we defined our problem as a multi-commodity cost flow problem and used the IBM Cplex Optimisation solver and SAS optimization tool to minimize the energy cost. IBM Cplex optimization solver is an optimization software package to optimize decisions, develop and deploy models using mathematical and constraint programming to improve the results. We defined our problem as a multi-commodity min-cost flow problem to find the energy-efficient network while minimizing energy cost.

1.6.5 Communication

The communication phase is a very important part of the research. We have kept in touch with researchers in academia, labs, and industry. Our whole work summarizes in a publication to let know about the work done. This phase will also include documenting a final report as a Ph.D. thesis. Moreover, all our publications are already defined above in the publication section.

Chapter 2

Literature Review

While looking back at the past years, it is crystal clear that our daily lives are getting equipped with modern devices such as smartphones, smart TVs, and smartwatches. These rapid developments are making our life easier and smart. The new technologies are growing fast with many more advancements to fulfill user's streaming requirements and real-time data traffic distribution. These applications are experiencing explosive growth, which is the main cause of burgeoning mobile traffic.

Researchers attempt to mitigate the traffic flow burden by finding out alternative data transmission network architecture. Several data offloading techniques have been introduced using cellular base stations, WI-FI hotspots, and vehicular networks, respectively. Bus networks have fixed bus routes and wide coverage which show the potential of forming the communication backbone along with the traditional network.

Many researchers have devoted their efforts to improving the resource efficiency of the ICT systems, but all are still dedicating to the telecommunications and Internet domains themselves. The consciousness of environmental problems leads to the highlight of CO_2 emission and greenhouse gases. The focus of this chapter is to review the literature on the concept of green networking, delay-tolerant networks, and heterogeneous networks. Then, the state of art regarding data dissemination in the heterogeneous network will be reviewed later. It is estimated that human modern activities [11, 13–15] radiate twice more CO_2 than regular procedures can ingest at the minute. Among all the energy-consuming industries, ICT's percentage is 2% in Carbon emission and 3% in global energy consumption [16]. On the other hand, 57% of power utilization of ICT industry attributes towards users and network devices in mobile and wireless networks [17, 18] In fact, this ratio is increasing tremendously, as global mobile traffic is 26% more every month as per approximations [19] in an increasing trend.

The research community's main aim is to maximize the performance of the communication system while producing sufficient information with minimum energy cost and controlling CO_2 discharge [20]. Researchers are gearing up for energy-aware communication technologies in heterogeneous networks with DTN Based approaches. Wireless Communication network [21] is expected to cooperate with the wired network for addressing performance challenges and energy utilization issues. Currently, wireless communication medium works under a heterogeneous environment with various wireless nodes (Pedestrians, Vehicles,) and overlapped coverage of wired network (Base Stations) [22].

While disseminating data in heterogeneous networks, Base Station is the main source of energy consumption from the operator side. Recent studies explain that the reduction in energy consumption is related to two terms: reduction in carbon emission and reduction in operational expenditure (OPEX). Various programs have been set up for achieving this magnificent challenge without compromising QoS. This work is mainly focusing on reducing operational expenditure while sustaining QoS attributes. Our research originates from three research areas as shown in Chapter 1. First of all, Green networking is the major notion area to work on energy efficiency, which outlines that how to utilize the resources efficiently and concentrate on the energy-efficient network, which ultimately promotes to get a sustainable solution for communication while consuming less energy. The second factor, Delay Tolerant

Network and Scheduled Vehicle, comes under the category of opportunistic networks. Opportunistic Networks tend to send messages in fixed nodes and mobile nodes because of mobility in their behavior. i.e. Delay Tolerant Networks, global mobile social network and vehicular network. They have received considerable research attention in recent years. However, due to the tremendously vigorous and changing network topology, the message dissemination usually follows the strategy of "store, carry and forward". Moreover, the messages can only be opportunistically transmitted to their final destinations with some delay and very fewer delivery probabilities. To improve this area and for a good delivery ratio, researchers are concentrating on efficient message transmission techniques. However, this strategy is useful in case of the loose time of requirements, but to sustain quality services, this topology will work in a heterogeneous network. Therefore, our next literature review enthused us to work on the heterogeneous network, which will be a combination of wired and wireless networks, wireless networks, and DTN Network or a combination of three. A detailed description of all three considered factors is below.

2.1 Green Networking

Green Networking is defined as the selection of energy-efficient networking technologies and better utilization of resources whenever possible. It has been estimated that 3% of the world's yearly electrical energy consumption and 2% of CO_2 emissions are caused by information and communication technology (ICT) infrastructure [23]. Moreover, it is estimated that ICT energy consumption [15] is rising at 15–20 percent per year. Specifically, 57% of the energy consumption of the ICT business goes to users and network devices in mobile and remote networks[19]. The connection between energy and execution is indicated by [24]. Efforts are done for energy efficiency by implementing virtualization, server consolidation, upgrading older products to new energy-efficient products, etc.

There is a very broad area to validate the concept of Green Networking, which is defined in the following terms:

- **Adaptive Link Rate:** As we all know that, in the case of an Ethernet link, energy consumption is based upon its utilization. The adaptive link rate has been designed in such a way that there will be low utilization of online resources and consumption will be less. This method can be used in two different ways: a) switching links to low energy consumption mode or sleeping mode. b) Rate switching, which means the reduction of line rate, according to low utilization.
- **Interface Proxying:** The main aim of interface proxying [25] is to delegate traffic from the mainboard CPU to low power consumption of the Network Interface Card. Such data can be offloaded from one system to another to utilize the resources and less consumption of energy.
- **Energy-Aware Infrastructure:** This section categorizes into energy-aware architecture and routing schemes [26]. In Energy-aware architecture, a new approach suggests amending structure over existing infrastructure. E.g. Grid5000 is a good example used by many researchers. Energy-aware routing aims to cumulate traffic over other network devices and allows other connected devices to be in OFF mode for rerouting strategies.
- **Energy-Aware Applications:** Applications are divided into 2 categories a) User-level Application b) Kernel-level network stack. In user-level applications [27], a strategy is used to test peers whose status is not known. Peers present their energy state and therefore energy efficient. The peer doesn't wake up idle peers if not necessary. In a kernel-level network, many applications get shared by others. They store data and don't send it immediately, which helps to reduce energy

consumption.

All over the world, various techniques are used for green network terminology. The Japanese government also demonstrates additional interest by introducing Green IT for power efficiency. Different applications range from little size, low modern observing of large scale energy compelled environmental monitoring. In network topology, energy is consumed at scanning, transmission, and data acquisition. All current approaches to green networking promise high energy savings at the cost of reducing network performance.

2.1.1 Green Technology and Concept for Next-Generation Networks

To better discuss the main issues in each field, we discuss many network type, which is given below:

1. **Wired Access network:** Wired access networks are a very critical scenario for reducing the overall carbon footprint of telecommunication infrastructures since they represent a large share of network energy requirements. Current green networking technologies [28] in this area include two approaches: a) Re-engineering Approach b) Dynamic Adaption Approach, the re-engineering of current technologies means replacing copper-based technologies with fiber ones to the maximum possible extent and as well as the design of power scaling mechanisms. Based on a model of a typical operator network [29–31] compared the power consumption of different broadband access technologies and architectures, especially DSL, FTTN+ VDSL, and FTTH (Fiber To The Home). Even though VDSL power management improves performance, the authors stated that there is still a clear advantage of FTTH concerning energy efficiency. In dynamic adoption approaches, they consider the trade-off between dynamic spectrum management and the rate

maximization of digital subscriber lines according to a given transmit power constraint of modems.

2. **Wireless Cellular Network:** Similarly, to the wired access network, also research approaches in wireless/cellular network infrastructures are mainly devoted to re-engineering current device platforms (e.g., access points, base stations, etc.), and to include support for the dynamic adaptation of network resources (and then of power requirements) to the actual traffic loads. In re-engineering approaches, specific research activities have been performed to reduce the energy wastes of fixed infrastructures of cellular networks (e.g., Base stations [32] and WLAN access points [33]). In more detail, in [34], dynamic approaches include interoperability with legacy protocols and devices. Another factor [35] to consider is that wireless networks mostly operate at significantly lower data rates than wired networks. Correspondingly, the need for buffer capacity [36] can be lower and acceptable latencies can be higher.

3. **Network Router and Switches:** As far as energy-efficient router and switch architectures are concerned, re-engineering approaches mainly focus on how reducing the complexity of internal architectures and using more efficient hardware technologies, Power-aware network investigates potential saving in design and routing [37–39]. The author use core and edge routers to investigate and ultimately results show that power consumption can vary by as much as an order of magnitude and there are substantial opportunities to control it. Various dynamic approaches [40, 41] have been introduced to reduce the carbon footprint of network equipment by following two main approaches, namely power-efficient design and power-saving design, respectively.

4. **Network Topology Control:** Power saving mechanisms [42] based on network and topology control [43, 44] are currently originated on the extension of the

traffic engineering and routing criteria to use. Researchers propose to reduce the network energy requirements by switching off unused links and nodes. Their main concern [45] is to move traffic flows among network nodes to find the minimum number of network resources (i.e., links and nodes), guaranteeing the best trade-off between end-to-end network performance and overall power consumption. Many dynamic adoption approaches have been proposed to switch off some portions of the core network, while still guaranteeing full connectivity and maximum link utilization.

5. **Green Ethernet:** Green Ethernet [46, 47] is a technology at the link layer, and it is highly widespread through various standard versions, at both customer and network sides. Ethernet interfaces [48] diffusion have attracted the attention of several researchers, since even a marginal reduction in the power requirements of Ethernet interfaces may potentially lead to saving a huge amount of energy. Many re-engineering and dynamic adoption approaches are working on energy-efficient solutions.

6. **End-users and Applications:** Many end-client applications have been proposed as far as green networking. They developed the NCP engineering to deal with P2P traffic of basic document sharing applications [49, 50]. In more detail, while centers around greening the conduct of BitTorrent customers, the creators proposed a model Gnutella-like P2P power for the executives. Nedevschi et al [51] exhibited that a complicated tradeoff exists between adjusting the complexity of the proxy, the measure of energy saved and the refinement of idle-time functionality.

2.1.2 Optimisation Techniques

Research on energy-efficient networking [52] has been going on for several years. Different energy-related issues have been altogether examined covering an extensive variety of subjects (routing, cross-layer plans, scope conventions, range portion, media access control conventions, resource allocation, scheduling, and so forth. Some of the techniques are followed:

1. **Energy Management in network connecting devices- routers and switches:** Over the last decade, various kinds of routers and switches are in use for high-speed networks. These routers and switches are designed with increasing capacity and performance, which also increased power usage. In [53], power density issues were considered and started focusing on designing aspects. Energy management depends upon: a) exploiting idle state, by putting switch/router on/off mode when no use b) clocking hardware at low speed by just trade-off between power and performance [54, 55]

2. **Energy-Efficient Communication Protocol** There is various publication on the energy-efficient protocol for wireless Adhoc network, wireless sensor network, multi-hop wireless networks, and delay-tolerant network in the literature. Many research works [56–58] are doing to improve performance in wired/wireless networks, heterogeneous networks. Energy consumption associated with the execution of transport protocol is one important issue to explore. They compared many protocols with new amendments [59, 60] to make it energy efficient. In [61], an energy-efficient TCP quick timeout technique was proposed for wireless local area networks to improve the efficiency of energy consumption by five times better than before. In the case of the Delay-Tolerant Communication protocol, Energy Efficient Epidemic Protocol [62] also considered performance and energy efficiency while communication. With the growth of the Internet (including wired networks) and the emergence of wireless networks such as wireless sensor networks, multi-hop networks, mesh networks, various energy-related publications have been released. All of them work on improving the

commodity-based network.

3. **Network Selection and Hand-Off:** The hand-Off Mechanism is to be used as one of the strategies used for green networking. This strategy keeps the connection active while moving from one network to another. Homogeneous network handoff is to be called horizontal handoff and on the contrary vertical handoff, the term is used for heterogeneous networks. This strategy consumes lots of energy and therefore network selection is being done using interfaces rather than keeping it alive all the time. Many researchers [62–65] worked for making energy-efficient network selection in homogeneous and heterogeneous networks. Researchers are still working on this aspect to make energy-efficient with good performance factors.

4. **Reducing Energy Consumption in Base Station/ Cellular Network:** Origuchi et al exposed that CO2 emission is due to energy consumed at the base station and mobile terminals. The trade-off between base station density and energy consumption is being analyzed by many researchers [66, 67]. This paper categorized that how much energy is consumed at a base station, which further gives direction to move towards wireless communication for energy efficiency. Power consumption at the base station is being predictable by all its constituent parts and core radio devices. While considering energy metrics, improvements in energy efficiency proceed in base station hardware, which is still struggling. Consequently, the proposed research determined to use fewer base stations and moving towards mobile nodes/DTN approach to forwarding data to the final destination. The important technique for reducing energy consumption in the base station is to improve the hardware energy efficiency of the transceiver and power amplifier. While considering the software feature of base stations, one approach to energy efficiency is by keeping the mobile network off during less traffic time. Several

approaches such as traffic requirements, channel information, and load balancing are proposed by Cellular Network. The ICT sector (including laptops, personal computers, telecommunication networks, data centers and computer networks, mobile devices) keeps on developing on a worldwide scale and the force will increment in coming years as more ICT equipment is being sent and utilized as a part of different segments of society.

In 2015, Huahong et al [68] introduced an energy-efficient technique named EBRP: An energy-efficient and buffer-aware routing protocol. They put their attention on an adaptive clustering algorithm that can achieve the optimal community division and extract the community attributes of nodes. They consider the sociality of nodes and dynamic changes of the attributes of nodes while selecting the best relay nodes to forward the messages. These attributes define the energy and buffer storage for messages. They evaluated the performance of their strategy with three real-life mobility traces

The study [69] has classified various technologies to truncate energy consumption in wireless communication. New inventions about smartphones and their features incorporate new architecture, new network management, and forwarding techniques. Therefore, it is important to make a shift from traditional spectral efficiency towards Energy Efficient designing and routing strategies. The future communication network is to be designed to offload traffic to other network devices while using comparatively fewer resources. Many researchers worked on energy efficiency techniques in wireless or wired infrastructure with changes in hardware requirements or routing strategies. This work proposes a new solution with guaranteed delivery and using less consumption of energy in a heterogeneous network. So far, we introduced Delay Tolerant Network with the tendency to store, carry, and forward. We use DTN where wired and wireless networks cannot approach or if there is a loose time of requirements. Numerous routing strategies have been invented for a good delivery ratio of data; a detailed description is in the next section.

2.2 Delay-Tolerant Network

Delay tolerant Networks (DTN) is a case type of Opportunistic Networks(OppNets), which is [70] developing as a critical method for correspondence between the remote heterogeneous devices because of their convenience, adaptability of operation, and calculation. All of the devices used for communication have increased their storage capacities, processing, and their communication technologies, Moreover, this communication capacity has enabled a novel class of applications extending from mobile networks to Vehicular Networks [71]. These applications work on the principle of forwarding messages from one device to another and are known as Opportunistic Network. DTNs [72] are inadequate versatile networks, where an end-to-end path may not exist. The main principle is to store, carry, and forward in the path towards the final destination. DTNs are often susceptible to the problem of high delay. Many applications are merging on the concept of DTN, for example, crisis management, wildlife monitoring, transport engineering, packet-switched network and disaster management, etc. Mostly the traditional ad-hoc networks and internet routing protocols don't function admirably in the event of OppNets where there is never a settled and dependable way amongst sender and recipient because of node's mobility, network allotments, node failure and other features which is reliable embedded in a dynamic wireless environment [73]. The communication in DTN depends on the contact opportunity between the nodes that emerge because of their versatility, and the store-convey and forward strategies. The message is gone to the intermediate nodes, which takes it closer and nearer to the destination lastly to the destination itself. On the off chance that the intermediate node does not locate an appropriate location that guarantees to take the message nearer to the destination, it keeps the duplicate message in its buffer until it finds a reasonable node to pass messages or finds the destination node itself [74]. Such type of networks leads to the long delay of messages.

Recently, many applications are emerging with the same concept of DTN. This concept is being advanced from Mobile Adhoc Network (MANET) but the basic difference between both is MANET nodes use TCP/IP for communication and DTN uses application-layer bundle (Transport and Network Layer) and uses the concept of store-carry and forward with other peers. It may take a long time to find an appropriate relay node, so need to use message carriers to store messages in the buffer for a long time. Many Opportunistic Routing Algorithm [75,76] has defined in terms of forwarding messages to the destination.

2.2.1 Routing Protocols used for DTN

- **Epidemic Routing:** It is a forwarding protocol [77] that works on the concept of spreading a message like a disease. A node starts spreading the message to all its neighboring nodes and keeps on repetition until the message reaches on destination. It consumes huge resources and provides optimal routing performance in terms of delivery ratio while minimizing delay. In this algorithm, the author considered a case of 45 nodes in the random waypoint model and their traffic patterns. They place an upper bound on message hop count and buffer space according to a single node. In such a way, increment bounds on all these parameters and applications just increase the probability that the message will be successfully delivered whether they have to consume more resources. Though, random pair-wise message dissemination among all nodes gives ensure of message delivery. This routing protocol involves two steps:

– Exchange of summary vectors: Every node contains an index of messages stored in its buffer, which includes unique message-ids.

– Exchange of messages: One node computes a set of messages carried by other nodes. The same is being done by other nodes as well. If such computed node is not empty, it requests its peer to transmit a message with its corresponding ID's.

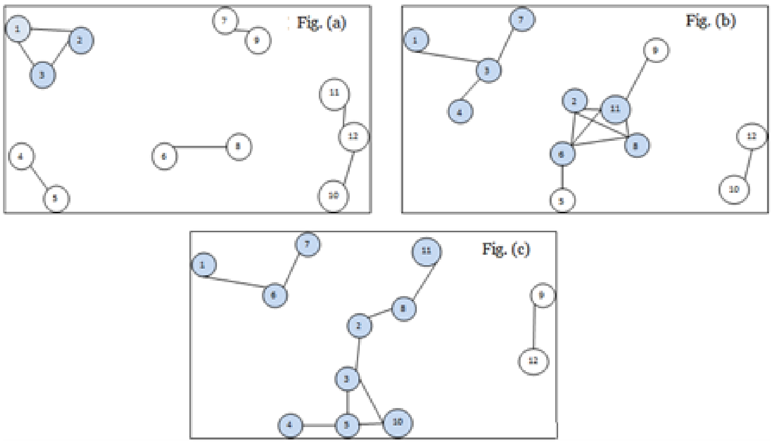

Figure 2.1: Epidemic Routing

While considering Epidemic as a benchmark, many researchers have given their hypothesis as a new invention. Zhang et al [78] worked on performance modeling of Epidemic Router with many other schemes by using a model. Due to the scattering feature of the Epidemic Routing protocol, it is being used in medical science. Matsuda and Taking [79] used this protocol wherein a relay node duplicates a message to another hand-off node with likelihood, and q is the probability of the source node to replicate a message of the relay node. With the variation of [80], the behavior of the Epidemic routing protocol changes subsequently.

- **Direct Delivery:** In this protocol [81] source node does not pass the message to the satisfactory nodes, yet rather keeps it with it until it comes directly in contact with the destination node. This plan is straightforward, simple to send and, uses the least data transmission and system assets for message exchange following every message are transmitted at most once to the destination node. Then again, there may be a long defers for message conveyance either for the situation the source never meets the destination or there may not be a quick contact between the source and the destination, however, a path exists through the center of the road nodes for the message passing. On the off chance that the source hub comes up short then, the message will be lost as there is a stand-out duplicate accessible in the system. In this plan's likelihood of conveyance is poor along these lines, it is not best for the circumstance where high conveyance likelihood is needed.

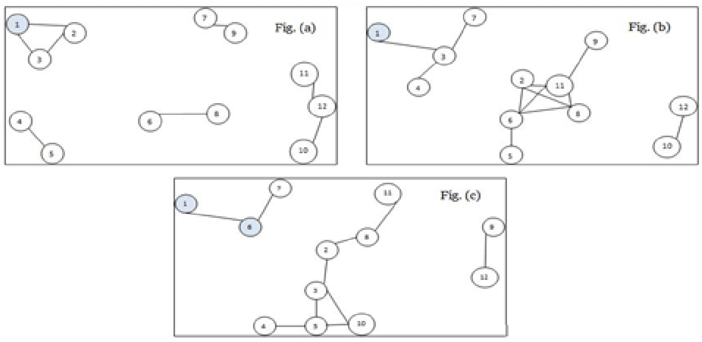

Figure 2.2: Direct Delivery

- **Spray and Wait:** This algorithm [82] is divided into two parts a) Spray Phase: where many numbers of copies are generated from the source and spread towards distinct nodes and they use direct transmission towards the destination. B) Wait Phase: If the destination does not get discovered, each of the distinct nodes uses the concept of direct transmission to reach the final destination. Initially, it uses the concept of Epidemic routing, but much better than Epidemic in terms of generating low contention specifically when high traffic load flows and highly scalable despite making any change in network size and node density. This strategy outperforms all existing algorithms in terms of transmission and delivery delays and finally got an optimal solution that is very scalable.

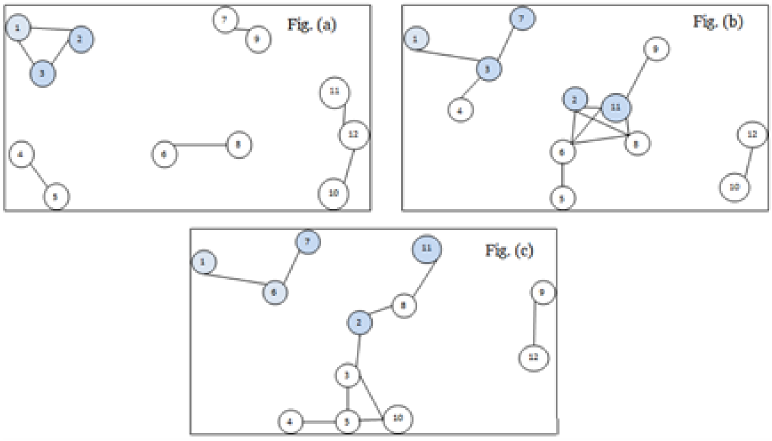

Figure 2.3: Spray and Wait Routing

- **Single Copy Algorithm:** Spyropoulous et al defined single-copy-based protocols for Opportunistic network where nodes forward a message only it knows the destination and transmits a single copy of the message once. Here, [83] utility function defines usability of nodes according to the number of meetings between all numbers of nodes and with their last encountered information. As soon as, high utility node is revealed, they use the approach of seeking and focus and finally reach the destination. Nodes take local forwarding decisions based upon their connectivity and prediction of future connectivity details. A combination of simple random policy and utility-based policy is followed to reach the final destination.

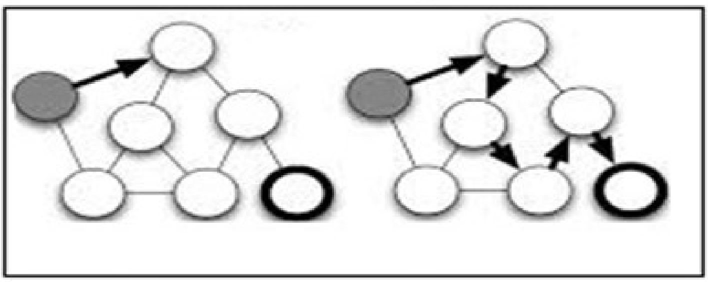

Figure 2.4: Single Copy Algorithm

- **PRoPHET:** PRoPHET (Probabilistic Routing Protocol uses History of Encounters and Transitivity) [84] uses non-random mobility and contact pattern with a probabilistic metric called delivery probability. It considers the history of previous contacts which is not to be considered as random and quite possible to identify mobility patterns. This model is based upon the prediction of the probability of each node for all known destinations. The predictability of delivery is denoted as $P_{A,B}$, and its range are defined as $0 \leq P_{A,B} \leq 1$.

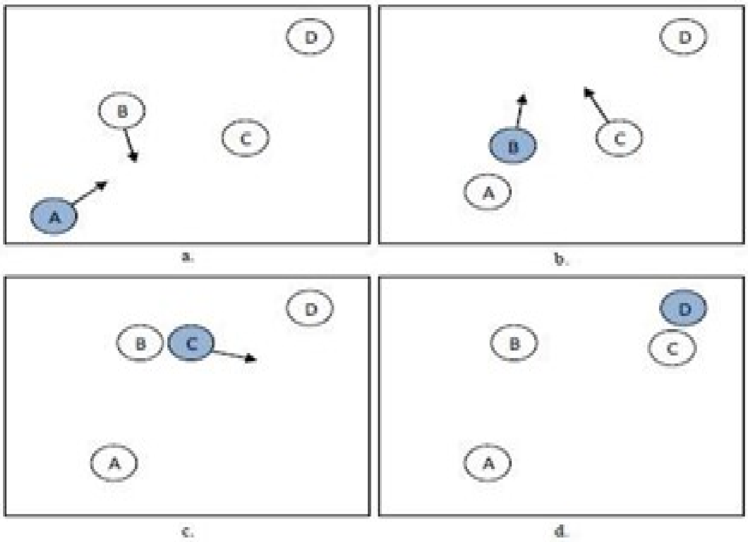

Figure 2.5: ProPHET Routing

2.2.2 From DTN to Vehicular DTN

Vehicular Ad hoc Networks (VANETs) have been an important research topic for many years. VANET has many special characteristics [85] e.g. Predictable mobility, High mobility, Variable topology in time and place, partitioned network, etc. VDTN consists of some unique features borrowed from VANET and DTN. In VDTN, some nodes (vehicles) work on the principle of the store, carry and forward. A Vehicle is also used as a carrier to carry the data from the source until destination and is called MULEs (Mobile Ubiquitous LAN Extensions). Mules help to extend the network coverage and the opportunities for communication. The proposed research is using the vehicle as a data carrier to transport it from one place to another in terms of energy efficiency. To implement our idea, data offloading can help to better understand the usage of vehicles in the transportation of data.

Grociz et al [86] used vehicle carriers for big data transfer. Due to increased internet traffic in recent years, they decided to exploit the existing worldwide road infrastructure as an offloading channel to help the legacy Internet assuage its traffic. Roused by the requirement for specialized adaptability and practical versatility, enormous organizations, associations, colleges, and administrative offices continually move their information and applications inside and between data centers to adjust remaining burdens, handle replication, and unite resources. They put their efforts into using conventional vehicles for offloading schemes, cost reduction, and capacity improvement. Assisted-DTN architectures involve various data carriers or forwarders ranging from buses to airplanes to compensate for the lack of continuous connectivity by bridging disconnected nodes. They justified that vehicles help to reduce traffic and cost with less delay.

While moving further with the concept of offloading data, Cheng et al [87] discussed Vehicular Wi-Fi offloading. Vehicular offloading relies upon drive-thru internet access opportunities; Drive-thru internet access [88] means the internet provided by all roadside placed APs to the moving vehicles. This internet access works on three-fold policies, high mobile vehicle gets connected quickly which ultimately limits the transfer of data in one connection. Therefore, packet loss possibility is more. This offloading scheme helps to sustain a connection for a long time for non-vehicle users. Vehicle users meet with many of APs with different connection time and then offloading scheme add in the prediction of Wi-Fi availability to transfer data. To increase the efficiency of drive-thru internet access, many more modifications came into research. In [89], a new mechanism was introduced to improve the connection time which enhanced the data transfer performance. They merged all the processes into one process with the name of connection establishment, where a network independent identifier was in use by both host and vehicle users. Moreover, this mechanism keeps sending probe packets periodically to distinguish wireless losses from congestion losses. In 2010, an offloading scheme [90] was named Wiffler. It was proposed to determine whether to defer applications for Wi-Fi rather than cellular networks. This strategy introduced delayed offloading in the availability of 3G and Wi-Fi networks. This switching is based upon the user's preference and information port names. Wi-Fi throughput varies according to delay period and prediction according to the estimated number of APs. Whitbeck et al. [91] proposed an infrastructure offloading scheme named Push-and-Track., this scheme determines the number of copies, the devices and the time of the copies to be sent. After receiving the content, it is being sent in an epidemic manner with acknowledgment sent back to infrastructure. TTL value estimation helps to know the exact number of copies to be pushed from infrastructure.

Work	**Message Direction**	**Goal**	**Offloading Type**	**Mobile Device Types**
MADNet [92]	Infrastructure → mobile device	Reduce infra load	Delayed	All infra-access all DTN
Drive-thru Internet [88]	Infrastructure → Vehicle	Reduce infra load and more strong connection	Non-Delayed	All vehicle Wifi-Access
Wiffler [90]	Infrastructure → mobile device	Prefer Wi-Fi over cellular strong connection	Delayed	All Wi-Fi and cellular-capable
HRS [93]	Mobile device ↔ mobile device	Offload infra., prefer DTN	Delayed	Heterogeneous infra.-access/ad-hoc
Kashihara [94]	Wireless Nodes → Vehicle	Reduce traffic congestion	Delayed	All Wi-Fi and cellular-capable
Push-and-Track [91]	Infrastructure → mobile device	Reduce infra load	Delayed	All infra-access all DTN

Table 2.1: Types of offloading with goal

In a paper [93], a new routing technique is used to offload data from an infrastructure-based network towards Delay Tolerant Network (DTN). Initially, the messages start disseminating from an infrastructure-less network and as the probability of successful delivery decreases, it shifts to an infrastructure-based network for assuring the delivery. These decisions are based on many factors like a fraction of the infrastructure-capable devices, the fraction of infrastructure-less devices, and the most important is message size. Unicast end-to-end communication is done between all mobile devices with the Hybrid routing system. The work in [95] introduced many offloading techniques in the cellular network to reduce network congestion. These offloading techniques are being categorized as delayed offloading and non-delayed offloading.

- Non-Delayed Offloading: Non-delayed offloading provides logical solutions as a Wi-Fi hotspot to lessen congestion and cost. Cellular Base stations and T2T approaches use wireless technologies to establish direct communication between devices and cellular to device communication. AP Based offloading is a user-driven approach,

- Delayed Offloading: In delayed offloading, content reception can be delayed up to a certain point of time but with good delivery conditions.

Sylvia et al [96] introduced energy-aware opportunistic mobile data offloading. Their main focus is to decrease the energy consumption while at the same time retaining the application throughput of an opportunistic network. They evaluated the performance of progressive selfishness which combines the merits of two energy-saving mechanisms which include duty cycling and selfishness. With the use of trace-driven simulation analysis, they evaluate the performance under two modes of nodes cooperation for the progressive selfishness behavior which helps to save energy up to 85% while sacrificing less than 1% with the distribution of density of node and availability of initial content.

In this paper [97], the author has deployed a cell base station in addition to a conventional macro base station to boost network capacity and energy saving. They focused on energy harvesting while sustaining the Quality of Services (QoS). They optimized the energy-aware traffic offloading scheme, On-Off state of SBS, and power control jointly to know the statistical information of renewable energy arrival and amount of offloaded traffic. In this scheme, multiple base stations have been set up in a heterogeneous network to satisfy quality services. The results achieve more than 50% power saving gain in comparison with conventional traffic offloading schemes. The author in paper [98] demonstrated Device-to-Device (D2D) Fogging, which works on the concept of mobile task offloading based on network-assisted D2D collaboration, where the network operator helps users to share the computation and communication resources among each other. They proposed an optimization problem for all the tasks of users to minimize the time-average energy consumption and incentive constraints of preventing over-exploiting and free-riding behaviours.

Now, all mobile phones and laptops are increasing data traffic every year and this trend is expected to continue further with all new developments. Therefore, Dimatteo et al [92] propose a solution to offload traffic from the cellular network towards the metropolitan WIFI access point, which is known as MADNet architecture. While transferring bulk data, this architecture is beneficial even in the case of a sparse WIFI network. MADnet consists of a total of six modules: Connectivity module, a Location module, Protocol module, Naming, and Forwarding module, Data Module. All of these modules are responsible for providing connectivity to users according to location, name, and then forwarding data. Every node of the system generates data to upload and requests content to download on another side. In such a way, at the time of downloading content, a user requests to the nearby base station with all the details (position, speed, and direction) which is known of all APs positions. The base station makes a list of all APs of that route and the node consults the particular AP to download the content. This list keeps in the storage of the node's system for future direct communication through Bluetooth/Wi-Fi.

2.2.3 Scheduled Vehicle/Public Transport

Vehicular DTN [99] is based on the concept of DTN. It handles non-real-time applications at low cost and unreliable conditions. Vehicles can be sued as a data carrier between terminal nodes either in rural areas or in emergency scenarios. VDTN follows the Open System Interconnection reference model. This protocol works on two layers of the OSI model: The physical layer and data link layer for functioning and data management. The Data plane aggregates data into bundles and transports it to the destination. At the source node, the Bundle aggregation layer aggregates packets and then the destination address gets convert into a VDTN terminal node address. Many techniques can be used for data assembly. Therefore, this strategy can help in the vehicle to vehicle communication.

We subcategorize Vehicular DTN into the scheduled vehicle or in other terms as public transport. Many researchers have worked on the scheduled vehicle to make networking more efficient to avoid random movement of the vehicle. Our research will also expedite public transport with the traditional way of communication for taking advantage of predefined schedules and predefined routes for a particular location. Data can be offloaded onto a public transport vehicle to use as a data carrier to transport it to another location.

Kashihara et al [94] proposed a data offloading technique to offload data, particularly to public transport vehicles by using high-speed short-range wireless communication. The motivation was to reduce traffic congestion because of the high volume of data. Firstly, the user checks all the requirements that are there any offloading spot, then fast and stable data transport. In uploading data, the user drops a large packet to the data port at any offloading spot or directly to the storage system of any bus. This drop decision is also depending upon delay time. If the delay time is acceptable then the only user drops it off otherwise not. After uploading, the bus carries data to the internet through a high-speed connection. In download, the user requests the server to deliver particular data to get it to any bus stop. If it is available, then will be delivered immediately otherwise the vehicle will carry it from the terminal and deliver it to the data port.

Michele et al [100] investigated the BUSNET algorithm that accomplishes viable directing in a transport network. It considers directing at a bus-line-level rather than a transport level. They prefer paths among bus lines and all the buses on fixed routes are considered as moving nodes. They use route contact oracle where every bus works on the DTN principle and can store, carry, and forward packets. A bus can carry and store data until a new neighbour is found and passes on until reach at the destination.

ALARMS [101] is one of the message scheduling approaches which uses message ferries to forward messages to achieve good QoS. Ferry nodes have their fixed route and move along those routes to share messages with gateways of each node of the route. It forwards its messages as per routing information for the next two rounds to reach gateway node. In such a way, the gateway node estimates the delivery delay of each message and schedule the message to be delivered by some other ferry to deliver it soon. They go for message prioritization and utilizes a scheduled ferry to deliver it.

The proposed research will introduce a scheduled vehicle as a part of communication if there is a loose time of requirements. Moreover, there are many rural ways where the wired/wireless network can't approach. Then, these scheduled vehicles can help to deliver messages with some delay. However, we can't ignore our traditional way of commination. In some cases, we can even lose our messages with the DTN approach and we don't want to compromise with our quality. Therefore, we will use the heterogeneous network to make communication more effective and energy-efficient.

2.3 Heterogeneous Network

Several wireless communication technologies have been developed so far. In particular, Bolcskei [101] developed BWA (Broadband Wireless Access) for residential customers to use telephone and Internet connectivity with a single access point (AP) that provides wireless connectivity to many users with a particular range. This approach is not suitable for rural areas with sparse user populations due to fewer numbers of users served by a single AP. The user-to-access-point ratio can be improved by increasing the transmission power of both user and access points. However, this enrichment couldn't provide sustainable infrastructure as it consumes higher energy and requires more expensive hardware.

Bejerano et al presented work [80] on efficient and low-cost infrastructure for connecting multi-hop wireless and wired networks. On these networks, some nodes behave like an AP and function as a gateway between the wired and wireless backbones. This work is subdivided into two phases, one is to design optimization where nodes are further partitioned into clusters and select a single AP node at each cluster. The operational part includes messages to be delivered through a spanning tree rooted at the access point of each cluster, which is called an adaptive delivery mechanism.

Lei and Perkins [102] proposed an integrated network (Ad hoc Network and Internet) with the use of Routing Information Protocol (RIP). It routes and forwards the datagram to a particular destination appropriately, but without keeping track of a return path. Therefore, QoS constraints are not satisfied. Jonsson et al [103] has given an architecture called MIPMANET (Mobile IP for MANET) which uses a MIP (Mobile IP) foreign agent and AODV(Ad hoc On-Demand Distance Vector). MIPMANET allows a visiting node to switch from one foreign agent to a new agent if two hops are closer to the new one.

Tseng et al [104] proposed an architecture that uses standard IP routing to relay IP messages and data packets without using MANET routing. All information exchange gets done by delivering Mobile IP messages without exchanging routing tables or ARP messages. The main disadvantage of the protocol is the cost of flooding advertisements which makes it a non-sustainable infrastructure. In this paper [105], the researcher is focusing only on the inefficient handling of Delay Tolerant Traffic. They want to shift traffic from peak hours with the advantage of delay-tolerant traffic nature. Therefore, two main strategies are used a) Offering incentives under a flat rate to those end users who shift their DT traffic. It is accomplished only by providing a higher than purchased access rate as a bonus b) Augmenting the network with additional storage such as Internet Post Office. It works based upon background load and the peering relationship between ISPs.

HYMAD: This Paper [106] proposed an HYMAD protocol (Hybrid DTN-MANET Routing for a dense and highly dynamic wireless network) which uses the concept of DTN between a disconnected group of the node while using MANET routing strategies. The best part of this strategy is its capacity to make connections according to connectivity patterns of the network. Intragroup delivery is being done by the ad-hoc routing protocol and DTN protocols contribute to intergroup delivery. According to connectivity, it decides its behavior to make a connection. In dense connectivity, it functions like traditional MANET. In very sparse connectivity, it behaves like a traditional DTN routing protocol. The eventual reason is to get good delivery in a heterogeneous network.

HSBR: Enhanced Hybrid Social Base Routing [107] is an optimal solution for combining features of both Dynamic Source Routing [108] and Social-Based Opportunistic Routing [109, 110]. This strategy is used for the highest success of packet delivery between source and destination from different start conditions and different continuance of mobile network. DSR path is being used to request routes and for opportunistic sending, data transmission follows social relation between nodes. In this work, the modified version of DSR routing is used which follows a route discovery/ request, route maintenance, detection of the last node. Social-based opportunistic routing is based upon the relationship between nodes according to their personal/private profile, contact profile (address book). HSBR establishes delivery of the message when standard MANET routing doesn't work properly or in a disaster situation. It's another advantage is to deliver messages with the expectation of delay. This work [111] focuses on hybrid networks which are based upon overlay network and Delay Tolerant Networks. DTN integrates with partial infrastructure to cooperate. Infrastructure devices work as a proxy for other devices to take messages through an overlay. Communication can be done with any type of infrastructure capable device (temporal infrastructure, continuous infrastructure access.

The Internet of things [112] are changing continuously according to the demand and requirement, therefore this work expanded existing routing algorithms with a new routing scheme, which consist of a heterogeneous set of nodes while taking into account two parameters: 1) Delivery Capability(L) 2) Number of Copies(C). This work focus on the use of opportunistic routing to provide various services like control in traffic, security, and environmental issues and making enterprise processes more efficient and effective. Performance is much better with the overall use of RSU as a high delivery capability and a large number of copies and same as pedestrians for. The given parameters help to get simulate the scenario and real comparison in terms of delivery ratio and latency with an improved version with various types of sensor nodes.

Many opportunistic routing [113] protocols have been proposed, but all of them get differentiated in terms of assumptions and types of a network for their evaluation. A heterogeneous architecture is being defined, including fixed infrastructure, mobile infrastructure, and mobile nodes.

- Fixed Infrastructure: Here, RSU (Road Side Units) gets positioned along the main roads of a particular area. These are fixed with lampposts, GSM Base Stations, and walls. It works as a backbone network that connects mobile nodes like phones with central servers, which distributes information from central's servers to other regions. Short Range Bluetooth and Wi-Fi 802.11 are the interfaces used for communication. Bluetooth is being used in the case of the RSU and regular phones for low range. The Wi-Fi interface helps to communicate between buses, trams, cars, and smartphones.

- Mobile infrastructure: Bus and trams with predefined route information come under this category. Bus and tram move fast, therefore Bluetooth is not the best mode for them.
- Mobile Nodes: Mobile nodes are those components that consist of cars and mobile phones carried by walking pedestrians. Here, we can't predict a path or route because of their unpredictable movement. These are classified into smartphones or regular phones which use Wi-Fi and Bluetooth Interfaces.

This paper [114] focuses on metropolitan environments intending to provide delay tolerant services to those areas where the end to end connectivity is not possible. It utilizes the CARPOOL plan to connect between ferries and gateways to compute routes to online gateways. Therefore, free public internet access Wi-Fi hotspot, and their connection were setups through public transport such as ferries, buses, and trams. DTN gateways are located in offline mode near all ferries stops to get an internet request from all end-users and in such a way act as a relay node. With Prior knowledge of contacts between gateways, a high delivery ratio with minimum overhead has been achieved. Therefore, the primary focus is on the scheduling of ferry access to the internet, easily get a schedule of ferries, and energy-efficient design of all computing operations. This methodology, however, does not adapt well to expansive deviations from the predefined plan and is not sufficiently adaptable to exploit opportunistic contacts between ferries.

In 2015 [115], previous work with an enhanced connectivity plan was introduced with the name of CRAPOOL+ which is having a smart mechanism of routing. This plan is being introduced for urban transport with prior knowledge of contacts between gateways and ferries to compute routes with traffic. In such a way, it provides a smart mechanism to select a route for the earliest delivery time with less replica overhead. It mainly concentrates on two dynamic mechanisms: a) Opportunistic contacts between ferries and provide a better route for earliest delivery b) Path recalculation if there is any change due to traffic congestion. Route selection depends upon so many things:

1. As soon as end users make internet requests to the offline gateway, CARPOOL+ selects an online gateway and classifies the best suitable gateway for this bundle, even when a middle gateway receives a bundle, it calculates the path again and updates its header to proceed further.

2. Even, if a ferry is late than the scheduled time, it stores bundles predestined to the particular gateway and calculates the path again.

3. In the meantime, offline gateways decide to recalculate the path before the next schedule ferry to forward messages according to the current opportunity if any ferry is delayed.

4. Even if there are two ferries in range, the decision will be according to the earliest delivery time for the bundles to forward.

This publication [116] gives a promising solution “Cost-Effective Multimode Offloading”(CEMMO) with the offloading of data to the best possible choice among the following three options to reduce overall cost in terms of energy efficiency, financial settlement, and user fulfillment.:

- Cellular delivery (3G Network): They assumed that the 3G network is always available and success probability is high in this option

- Delay-Tolerant Offloading: Here, every user's probability to get Wi-Fi before the DTI (Delay Tolerant Indicator) expires
- Peer-Assisted Offloading: Data will be offloaded through intermediate mobile devices. It's not only be used for offloading data for uplink but also independent of its content and popularity.

In such a way, while applying the mobility and connectivity plan of peers based on the Markov process, CEMMO gives authority to a cellular operator to take the best decision of the most effective mode of communication according to cost minimization. In such a way, an offloading percentage is 59% towards mobile data traffic, and cost reduction calculation is 16% over DTO, which is an improvement of 31% on energy consumption. In this model, user mobility during any time interval t works on the concept of the mobility prediction model, the next region that will be visited by a user during a time interval is assumed to solely depend on the previous one. Therefore, the cost-effective decision can be taken according to the offloading ratio, the average cost per MB, and the average cache size. The average cost per MB is calculated as below:

Avg Cost =($\alpha\times$ Data Transmitted 3G+$\beta\times$Data Transmitted Wifi) 1/(Total Data Transmitted)

Where α is the transfer cost per MB through 3G and β is the transfer cost per MB through Wi-Fi. The proposed work is focusing on energy-aware data dissemination techniques by utilizing existing public transport. Table 2.2 shows the comparison of our proposed public transport based data transfer framework with other existing works.

2.4 Network Selection in Heterogeneous Network

A heterogeneous network environment contains many types of networks, such as traditional core networks, LTE, UMTS, or vehicular networks. But the selection of a

Previous work	Storage Capacity	Transfer Frequency	Communication	Framework	Message Direction	Route Requirement	Reliability of Trans Task	Machine Learning	Energy Efficiency
Shah et al [117]	Undefined	Undefined	Wireless	−−	Unidirectional S → D	Fixed Route	×	×	×
Cheng et al [118]	Undefined	Undefined	Radio Communication	−−	Unidirectional S → D	Actual Flight Path	×	×	×
Baron et al [119]	Undefined	Undefined	Radio Communication	−−	Unidirectional S → D	Vehicle Trajectory	×	×	×
Palma et al [120]	Undefined	Scheduled Own resources	NA	Emulated Environment	Unidirectional S → D	Fixed Route	×	×	×
Banola et al [121]	Undefined	Scheduled Own resources	LTE	Emulated Environment	Unidirectional S → D	Fixed Route	×	×	×
Usbeck et al [122]	Undefined	Scheduled Own resources	Radio Communication	Emulated Environment	Unidirectional S → D	Unspecified Network	×	×	×
Amazon Snowball [123]	100 TB	One Time and Scheduled on demand	Wired	Amazon Big Vehicle	Unidirectional S → D	Limited Specialised regions	×	×	×
Naseer et al [124]	Independent disk size	Scheduled by CC	WiFi-Direct	Modelling Data-Driven	Unidirectional S → D	Vehicle Trajectory	✓	×	✓
Coutino et al [125]	Undefined	Scheduled Own resources	Radio Communication	One Simulator	Unidirectional S → D	Unspecified Network	×	×	×
Murk et al [126]	Undefined	Scheduled Own resources	Wired	AnyLogic PLE	Unidirectional S → D	Unspecified Network	×	×	×
Maria et al [127]	Undefined	Scheduled Own resources	LTE	AnyLogic PLE	Unidirectional S → D	Vehicle Trajectory	×	✓	×
Proposed system	Independent of disk sze	Scheduled by CC	Wifi-Direct	Modelling Data-driven approach	Unidirectional S → D	Fixed Route	✓	✓	✓

Table 2.2: Comparison with existing techniques

suitable network is a challenging issue in the heterogeneous environment [128, 129]. Many users have different criteria and different preferences and based upon these preferences, the decision for network selection is being made. The network selection procedure completes in three steps. The first step is finding available networks to select from many different networks by collecting all the information such as network performance, network range, network bandwidth, services. Second, considering all different criteria of network selection, based upon the criteria which network should be selected and when to switch as different preferences. Third, enable access for all the networks and make the selection for the goal decided. There are different kinds of methods for network selection such as Multi-Attribute Decision Making (MADM) [130]. This paper explains all the mathematical theories for modeling network selection and discusses different combinations. All handover strategies include many issues such as mobility, decision algorithms, and performance metrics. MADM method applies to the set of alternatives to choose from which are considered as per their attributes. There are many popular MADM methods, some of them are below:

1. SAW(Simple Additive Weighting): SAW [131] is one of the simplest and most often used methods to calculate an overall score based on the weighted average. It consists of a normalizing matrix and evaluates the score for each alternative with the weights of relative importance.

2. TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) [132]: This is also one of the popular methods for network selection. An alternative is positioned based upon the relative closeness to the ideal solution and farthest from the worst solution.

3. AHP(Analytic Hierarchy Process) [133]: AHP method is popular than other methods because its utility outweighs other research methods. AHP method is a hierarchal structure and attains a goal as per different criteria and alternatives. A pairwise comparison matrix is constructed with a discrete scale from 1to 9 for evaluation

4. GRA (Grey Relational Analysis) [134]: GRA method is useful for uncertain or incomplete information. This method is used to rank the candidate networks and selects the one with the highest ranking.

Many researchers have used these methods for network selection. SAW and TOPOSIS shoes almost similar performance but varies based upon different traffic classes or services. All these methods depend upon the weight assigned to all the criteria. Kessar et al [135] introduced the Always Best Connected (ABC) concept, for providing the best connectivity to all the applications always. The handover decision is being taken on regrouping criteria like network, terminal, user, and services. All these criteria help to make a handover decision and provides the best connectivity. Another network selection mechanism [136] was used in combination with AHP and GRA to trade off network circumstances, services, and user priorities. AHP was used for weighing based upon user preferences and GRA was used for ranking network alternatives. In [137], Goyal et al proposed a network selection method using triangular fuzzy numbers along with AHP for different applications(voice, video, and best effort). They derived the FAHP based network selection method using a non-linear fuzzy optimization model for weighing based upon different alternatives and criteria. They also used a utility model for user satisfaction for different attributes. They calculated network scores for different methods and compared the MEW methods to give better results in comparison with other methods.

Some researchers have used utility theory [130] for network selection. Utility functions are originally defined in economics to define the degree of satisfaction. Different users have different preferences and satisfaction levels for the same attributes and criteria. Therefore, these utility functions are designed to convert each attribute to a utility value, then we calculate the complete utility value for all the networks and then accordingly rank the network to achieve maximum satisfaction. Not only this, some literature [138] used MADM and utility functions all together to target the most suitable network. This method provides good quality of services and reduces abnormal selections.

Liang et al [139] introduced an integrated approach for network selection using utility functions, entropy method FAHP, SAW, and TOPSIS. They calculated the utility value for each attribute as per different services and then applied the entropy method and FAHP for the weighing value. And then the candidate network was selected based upon all combinations and user satisfaction. In Liang's other work [140], a user-oriented intelligent network selection scheme has been proposed, where five different modules are considered for network selection. One of them is input which includes utility function, next is user preference calculation using FAHP to calculate weighing of judgment. Then, the network score is being calculated using a fuzzy neural network. Next, the output model looks for the difference between actual and output values. At last, the learning module as per the error helps to correct the membership function for neural structure. Yu et al [141] proposed network selection using multiservice multimodal terminals. They also used utility functions for multi-services for user satisfaction, network attributes, and service characteristics. To calculate the weight, they used entropy and the FAHP method. Moreover, the TOPSIS method was used for network ranking. In such a way, they select the optimal network by taking into account different factors.

We have been presented a vast literature on existing approaches and architecture for the energy-efficient network architecture in a heterogeneous network. The existing literature outlined the key ideas and the solutions proposed to achieve their goal that helped us to understand the need for our proposed solution. We have analyzed that the researchers have started aiming at the Internet of vehicles (IoV), in which smart vehicles are equipped with computing and storage capabilities to communicate with surrounding infrastructure. Therefore, we introduced the concept of the Internet of buses (IoB), where public buses enable a service as a data carrier.

2.5 Summary

In this chapter, we have first reviewed green networking, which is the main motive of our research. Many approaches have been discussed for energy saving. However, these approaches are not sufficient with the tremendous growth of data demands in every sector. Thus, a delay tolerant network (DTN) is introduced to tackle this issue and can use the features of DTN to store, carry, and forward data as per the requirements. There is vast literature on DTN routing protocols to forward messages with different movement models and different routing techniques. These routing protocols also introduced the concept of data offloading to handle network congestion. Next, we discussed the heterogeneous network, where different devices can connect to different networks and communicate with each other. We also reviewed MADM methods for network selection in a heterogeneous network. These methods help us to find an optimal network based upon different services and user's preferences. We presented the research design and methodology used in each contribution in this thesis. We have used the Design Science Research Methodology (DSRM) for conducting this research. This methodology helps to address specific problems and finding the best solution encompassing principles and procedures to achieve our research objective. We presented all the phases, methods, tools used to evaluate and validate our modeling technique. All of the phases of research methodology is an iterative process for effective and potential outcomes.

Chapter 3

Public Transport Assisted Data Dissemination System: An Alternative Communication Channel

3.1 Introduction

Nowadays, all mobile devices are equipped with wireless network interfaces and these affordable wireless communication options are introducing new demands in the wireless network leading to the digital society. Smart City research relies on advanced technologies such as the Internet of Things (IoT) and communication technologies to deal with big data-driven applications [142]. Given the current situation, mobile operators may not have adequate bandwidth to cope with the amount of traffic generated by their users. On the other side, researchers are working on these challenges and provide us insights into understanding sources of big data with their generated traffic phenomenon and ultimately looking for solutions to mitigate traffic problems. Many operators have invested in the radio access network or cellular but again a very expensive way with less customer satisfaction.

Recently, much attention has been focused on exploiting the unrestricted scale to leverage the traffic burden from the traditional network to other networks, which is so-called data offloading. This technique helps to reduce the amount of data being carried on the traditional network and free bandwidth for other users. According to the white paper of the Cisco Visual Networking Index (VNI) [143], 51% of total mobile data traffic was offloaded onto the fixed network through femtocell or WiFi in 2015 worldwide. So, it is possible to offload data from the network to another available network as per the user's preferences. Some researchers initiated aiming at the Internet of Vehicles (IoV) [144], where smart vehicles get equipped with computing and storage capabilities to communicate with surrounding infrastructure. Same way, we are also using the concept of data offloading into our work and introducing an alternative communication channel along with the traditional network to handle this explosive growth In the proposed work, we are enlightening a new term as the Internet of Bus (IoB), where public buses enable a service of data carrier among the smart city by introducing a Public Transport Assisted Data Dissemination System (PTDD), where opportunistic sensing comprises delay-tolerant big data collection, processing and disseminating from one place to another place around the city. In this heterogeneous network model, data will be offloaded from traditional telecommunications networks towards the scheduled public transport networks by using delay-tolerant network techniques.

The public transport network operates as vehicle-assisted delivery with buses and bus-stop as nodes of this network. While divesting data from source to destination, people generally use existing infrastructure and forwards messages to deliver until destination. We are going to assess the existing public transport and road infrastructure to utilize them for sustainable communication and networking. We demonstrate a mapping algorithm to represent the complexity of the road network and logical links. We, to study the characterizations of the public bus system in terms of delay, capacity, and throughput and their potentials for data transmission. The offloading overlay moderates the complexity of the substrate network and makes the allocation of vehicles tractable. As a summary, the main contributions of this chapter are the following:

- **Public Transport Assisted Data Dissemination System (PTDD) as an alternative communication channel:** Identify the characterizations of the public transport bus system that currently exists and determine bus daily movement patterns to form a data transmission network named as Public Transport Assisted Data Dissemination System (PTDD).

- **Network Capacity Analysis of Auckland Public Transport Network:** We evaluate Auckland's public transport bus mobility patterns to analyze their potential or capacity. The results show that utilizing existing public transport, we can accommodate big data transfer using public buses.

- **Bus Arrival Time Prediction Model using Advanced Neural Network (NN):** Advanced Neural Network is being applied to analyze the bus arrival time based upon historical data. The obtained results will help to identify the difference between scheduled and predicted arrival time to estimate the accuracy to utilize public buses for data dissemination and will help to allocate data onto buses as per their stay time.

The remainder of the chapter is structured as follows. Section 3.2 illustrates the existing work done in the area of another mode of communication using vehicles. In Section 3.3, we introduce Public Transport Assisted Data Dissemination System (PTDD) to utilize public transport effectively for data dissemination to analyze the great potential behind using public transport network with bus arrival time prediction model using ANN. In Section 3.4, we assess the network of Auckland public transport that how much data can deliver the all-around city. Section 3.5 gives detailed results on the great potential to use the transport network and bus arrival time prediction. Finally, Section 3.6 draws the summary of this chapter.

3.2 Background

Smart cities are embedded with the smart devices and terminals in the cities to accumulate and handle information. However, it is very challenging to attain a high-level quality of collective services due to a lack of processing capability. Therefore, the research community's main aim is to maximize the performance of communication systems, however, on the other side, there is also a challenging issue of bulk data migration over the internet network. On the other hand, a huge surge in internet traffic has raised many concerns over the strength of the infrastructure that keeps things running. Accommodating this evolution requires an alternative approach to alleviate this pressure on existing infrastructure. Many of the co-operative approaches [145] have been proposed for data gathering from different locations. This approach finds [146] optimal logical links to transfer data in bulk using vehicles. In his another approach [119] , the author plots an overlay network over an existing network and all the moving nodes act as a relay node. The results proved that a huge amount of data can be transmitted using road infrastructure.

The paper [115] focuses on metropolitan environments intending to provide delay tolerant services to those areas where an end to end connectivity is not possible. It utilizes the CARPOOL plan to connect between ferries and gateways to compute routes to online gateways. Therefore, free public internet access Wi-Fi hotspot and their connection were setups through public transport such as ferries, buses, and trams. DTN gateways are in offline mode near all ferries stops to get an internet request from all end-users and in such a way act as a relay node. With Prior knowledge of contacts between gateways, a high delivery ratio with minimum overhead has been achieved. For heterogeneous networks and to connect parked vehicles to the internet, the authors [147] proposed a programmable architecture called a software-defined vehicular network based on the connected dominating sets of vehicles. In another piece of work [148], the author proposed a code transportation technique to transmit data all over the smart city. When any of the moving vehicles enters the range of deployed sensors, sensors synchronize their pushed code with the cloud center and start transmission onto the vehicle with a data mule. Naseer et al. [124, 149] also proposed a data forwarding scheme based on using a moving vehicle for data pickup and delivery. The strategy also used conventional networks and moving vehicles based upon their trajectories to collect data with delay tolerance to send from one place to another. A comparison illustrates that energy cost is less in a vehicular network in comparison with cellular networks.

3.3 System Architecture

3.3.1 Public Transport Assisted Data Dissemination System (PTDD)

The proposed framework depicts the PTDD, which consists of smart cities that are equipped with wireless sensors and data centers to handle massive data dissemination for several categories of applications as shown in Fig. 3.1 using a set of buses picked up at each bus stop. PTDD consists of the central controller(cc), Data Centre (DC), Roadside Units (RSU) deployed at the bus stop and buses. Smart meters, Video surveillance data, air pollution data are some of the delay-tolerant applications and can delay ranging from seconds, minutes to hours. Over the last few years, Vehicles [150] are being used as mobile nodes to create a mobile ad-hoc network. They move randomly and communicate either with moving vehicles or fixed equipment such as Road-side Units (RSU's). This alternative communications network layer of public transport networks can be any transport mode. All nodes in the network can be categorized into two types: i) fixed nodes, such as bus stops; ii) mobile nodes, such as buses, tramways or subway.

The traditional way is to use a traditional network to handle this data. However, this alternative communication channel layer of public transport networks can be used for

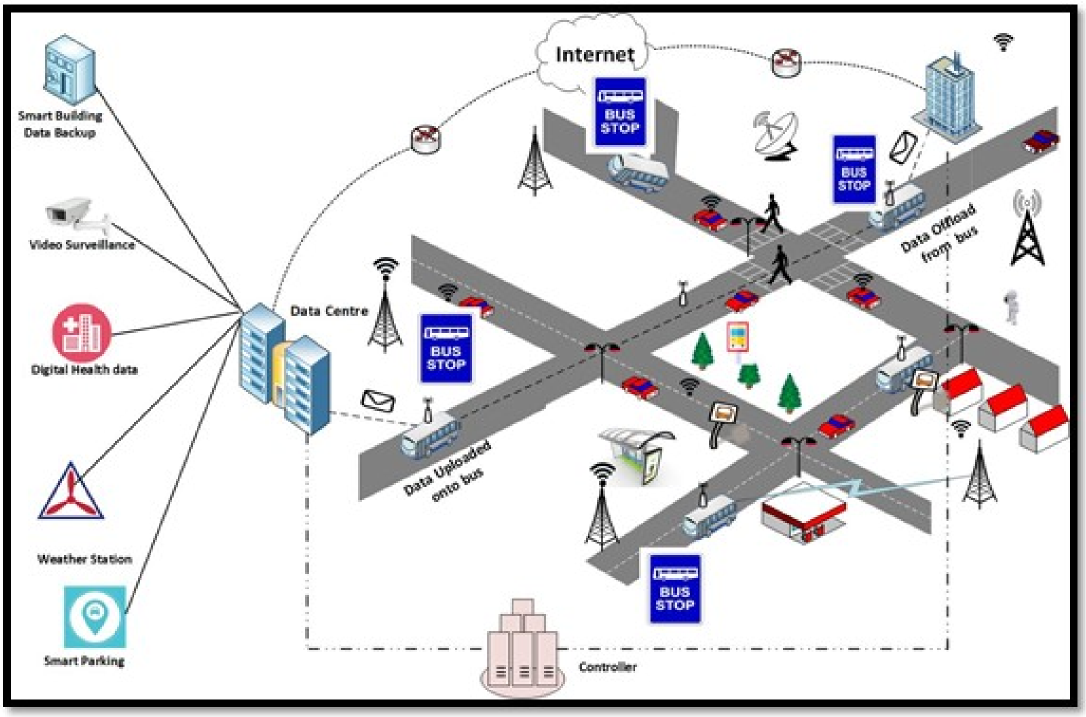

Figure 3.1: Public Transport Assisted Data Dissemination System (PTDD)

large-scale data transfer accumulated at each data center using a set of buses picked up at each bus stop. This channel is being technologically advanced from DTN working on the paradigm of store-carry-forward. The generated data will be accumulated at the data center near bus stops. The central controller will be taking all decisions to upload data onto selected buses as per bus route and delay-tolerant indicator (DTI). DTI determines the time for how long data transmission can be delayed. All public transport vehicles are equipped with removable storage devices and on-board units. Moving further, the collection of data will be at all bus stops where buses stop for a long or short duration during their travel route, and data will be uploaded and downloaded on these parking spots only. It is important to be into the range of interface for better and fast communication between bus stops and buses. The network used for communication is periodic and predictable as per the scheduled timetable.

In our proposed work, we will consider the scheduled buses to carry data from one place to another place. Just because most of the countries have a reasonable wide public bus system, these buses are scheduled, and delay and reliability can be controlled to some extent. Some works have been done to leverage public transportation networks to create a wireless infrastructure. It is an interesting study to be explored how efficiently we can take advantage of this bus system. For example, an organization needs to daily send massive data from one location to another location for backup, information sharing, content delivery, etc., which is being sent through network infrastructure (wired/wireless network). There is also public transport available between both places approximately every 30 minutes and best utilize its existing transport infrastructure as a part of data communication. For our PTDD, we assume that,

- The road network topology is stable. For a bus route, there is no change in bus stops for a long time and bus movement patterns are fixed as per their predefined schedule. The mobility patterns of buses are predictable as it travels on a fixed schedule back and forth between two bus stops.

- To use public transport as another communication network, we assume all buses to be equipped with an On-Board unit for storage and a wireless interface for communication. RSU will be deployed at each bus stop. These bus stops will be considered as parking/offloading spots.

Recall the objective of our chapter is to assess the concept of the public transport network to efficiently utilize them to remove the bottleneck in the existing infrastructure network. We will be focusing first on the capacity of public transport carrying the data and offering the same performance as the one resulting in transferring the same amount of data on the traditional network. The buses are to be operated for point-to-point data transfer from a specific bus-stop to a specific bus-stop. The network used for communication is periodic and predictable as per the scheduled timetable. We will be investing data offloading concept from bus stops towards buses with the help of graph metrics. To determine this, we will be analyzing the bus routes, bus numbers, and their movement pattern for the region as per the different times of the day.

3.3.2 Transport Network Capacity Analysis using Graph

Many real-world systems are represented by a graph. The objects can be represented as nodes of a graph and the relationships between these nodes can be represented as edges of the graph. We will be looking for the scale of the transport network for this analysis. The graph formed by such systems can then be further elaborated to know more detailed measures and meanings to make better judgments. This network analysis provides researchers a great help for in-depth analysis of these complex networks that are often too difficult to analyze without simplifying them. Some systems representation does not affect the change in time, on the other hand, some system captures the time dimension of the system and are called the time-varying graph. We will be focusing on a time-varying graph only as our study is based upon a fixed timetable of any transport network.

Traditionally, networks were being evaluated using models and metrics only excluding their dynamic nature of the network. We model our transport network structure by a directed graph $G(V, E)$, where V represents nodes such as buses and bus stops, and E denotes edges like bus lines.

In our model, not only structural representation is important, but we must also consider temporal variations as well. As discussed, we will be representing our road network as a time-varying system. The life span of any temporal network is $[0, T]$, where $V = [1, 2, 3 \dots n]$ and represents all nodes. Formally, an edge $e = (S_i, S_j)$ in E define a bus service between two end-stops. Then, we can describe our time-varying graph:

$$G = (V, E, T, \rho, \gamma) \tag{3.1}$$

where $\rho: E \times T \rightarrow 0, 1$ denotes a presence function to indicate the presence of an edge between two different stops that it exists or not. γ indicates the duration of the existence of that edge [151]. Besides, each vehicle v is associated with a trip, denoted $trip(v)$, which is a time-stamped trajectory:

$$trip(v) = (S_0, T_0), (S_1, T_1), \ldots .(S_n, T_n) \tag{3.2}$$

such that a vehicle v should arrive at the stop S_i along it is trajectory at the time $T_i = (V, S_i)$. Most researchers have focussed on many ways for numerical analysis of the transport network.

Overlay Transport Network with existing infrastructure

The overlay transport network is a logical representation of the road network as mentioned before as $G(V, E)$. This overlay network represents bus route and respective bus stops and their connection for a simple road path. Note that, multiple paths can connect different stops as shown in Fig. 3.2.

Elements of Overlay Network

In this section, we characterize the logical links of the offloading overlay into network quantities. The network quantities we consider in the following are relevant to know the great potential behind using public transport

- **Capacity Estimation:** We define the capacity $c(i, j)$ as the maximum amount of data that can be transported from i to j by buses in a time frame as follows (in Mbit/s)

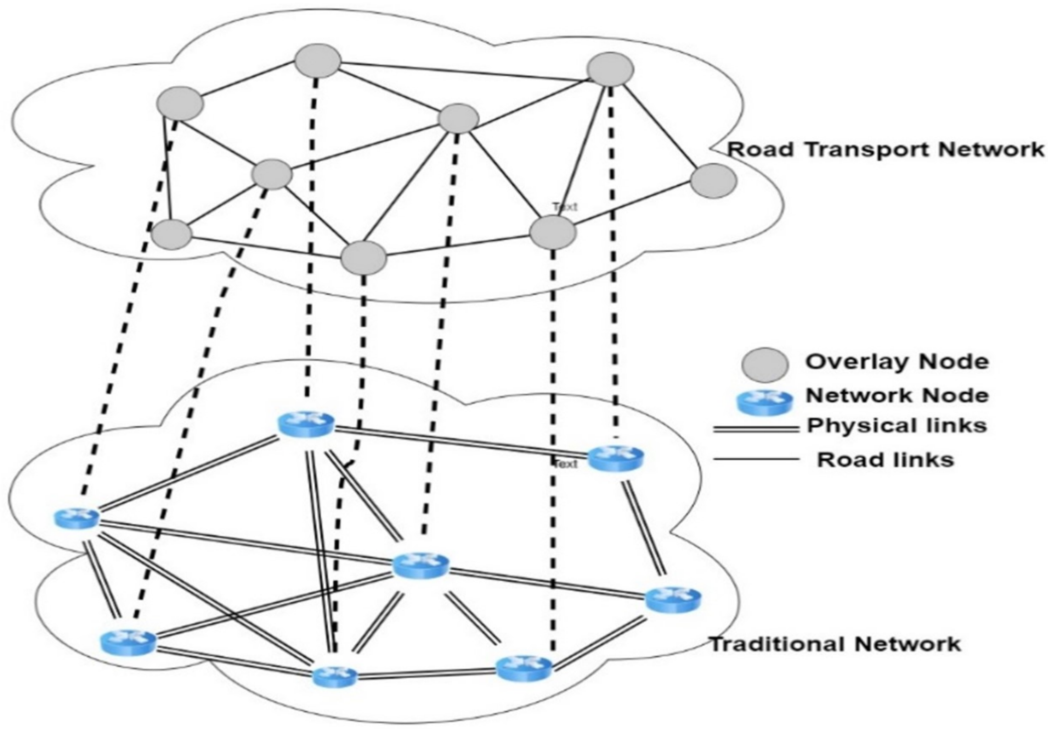

Figure 3.2: Overlay Network and Traditional Network Representation using Graph

$$c(i,j) = Bs_i \sum_{t \epsilon i,j} V_t \tag{3.3}$$

Where s_i is the storage capacity (in Mbits) of every bus, B is the number of buses participating in carrying data with storage for particular demand between locations i and j in the time T (in hours) and V_t is the number of buses per unit of time going from i to j. The capacity of a transport network is defined in terms of feasible throughput of data dissemination using buses. To elaborate more, we define it in two different ways:

(Definition1) Feasible throughput: We will be considering the throughput of each bus is achievable for $\lambda(n)$ bits per second if there is a bus available for that particular route for data transmissions, and every bus can send $\lambda(n))$ bits per second to the decided place.

(Definition 2) As per Knuth's notation, the capacity of the transportation network is of order $\theta(g(n))$ bits per second if there are deterministic constants $c > 0$ and $c < +\infty$ such that:

$$\lim_{n \to \infty} Pr(\lambda(n) = c(g(n))\text{is feasible} = 1$$

$$\lim_{n \to \infty} Pr(\lambda(n) = c(g(n)) \text{ is feasible} < 1$$

To determine this, we will be first analyzing the bus routes, bus numbers, and their movement pattern for the region as per the different times of the day to analyze their capacity to carry data.

- **Travel Time:** The travel time $t(i, j)$ is given by the sum of travel times t_{ij} between i and j and the waiting time γ_{ij} at each intermediate stop of that route.

$$t_{i,j} = \sum_{i,j \epsilon S} t_{i,j} + \gamma_{ij} \tag{3.4}$$

3.3.3 Static Aggregated Graph (SAG) for Analyzing Great Potential

These SAG graphs aggregate all the information from the temporal network and then further produce a single static aggregated graph. These graphs consist of information regarding all the contacts that occurred between the pair of vertices, the stay time, and the contact occurrence as per the time-varying system. A static aggregated graph sums up all the edges during selected window time and being called static over that time interval. Fig. 3.3 below shows an example of SAG with a time-varying system. In our work, buses will be moving as per the time-varying system and representing the SAG graph as per their scheduled timetable. It demonstrates that the final graph includes all of the edges or in other words, covers all the paths between A and F. However, as per different timings $T = (1, 2, or 3,)$ there are no such path exists. For example, a bus imitates its journey at 9 am and covers its route only. For different timings., different routes will be covered, and finally, if we aggregate, for those regions, we come across all the routes. An aggregated graph can be represented by an adjacency matrix $A = [A = a_{i,j}] \in R, N \times N$, in which the entry $a_{i,j} = 1$ if at least one contact $(i, j, ,)$ has been registered in $[0, T]$ between i and j, and $a_{i,j} = 0$ otherwise. If there is co-location or collaboration between graphs, the corresponding adjacency matrix is called symmetric. On the other hand, when directionality is applied, the adjacency matrix is non-symmetric. Our public transport adjacency matrix is non-symmetric as buses move in a fixed direction and route. The static aggregated graphs and the metrics proposed for their analysis is a structure to know the functioning of the systems as per temporal characterstics.

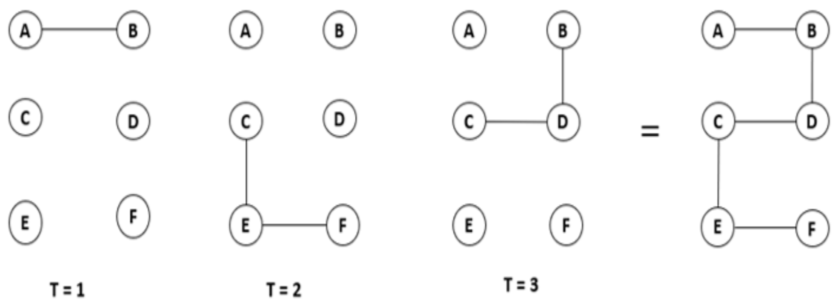

Figure 3.3: Static Aggregated Graph as Per the Time-varying Network

3.3.4 Bus Arrival Time Prediction Model using Advanced Neural Network

In the proposed work, the objective is to apply machine learning techniques to develop a bus arrival time prediction model. The model is developed to give accurate bus arrival information to apply proactive strategies for data dissemination. Recent studies on bus arrival time predictions reveal that the ANN model outperformed in terms of accuracy and robustness [152]. To predict bus arrival time prediction in our work, an advanced neural network model was performed using input features of the transport agency. This model is comprised of large numbers of highly interconnected elements such as link-based or stop-based transport data. In the information processing system, the elements are called neural who process the information like our brain process information. The neurons with n inputs calculate their output. Such frameworks "learn" to perform activities by thinking about models, for the most part without being customized with any explicit standards. The procedure records each in turn and learns by contrasting their prediction of the record (largely arbitrary) with the known real record. The errors in the output from the first prediction from the main layer are taken care of back to the system and used to alter the model's computation by changing the weight of the associations for the repetition process. These steps are repeated multiple times.

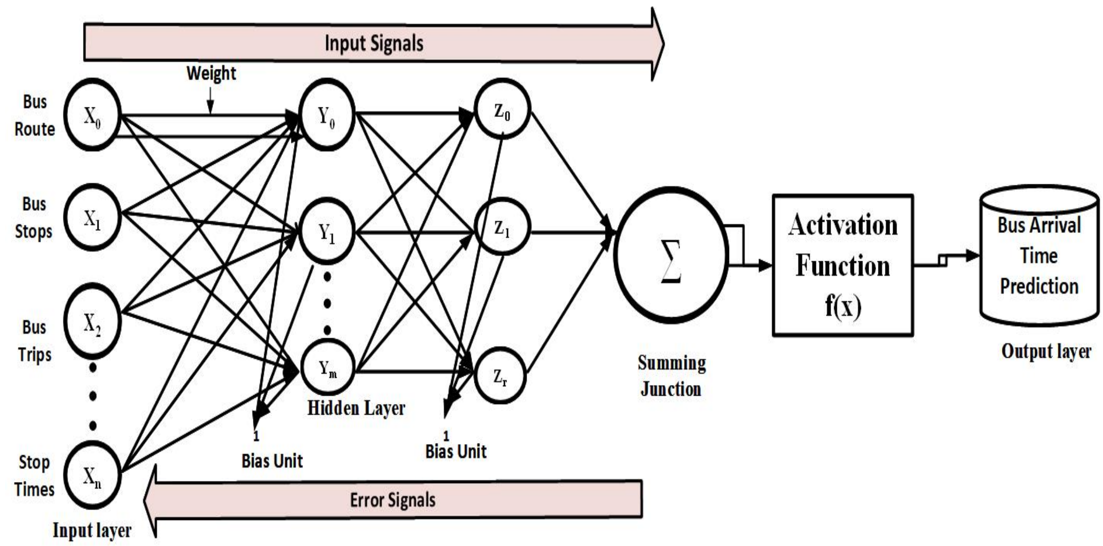

Figure 3.4: Bus Arrival Time Prediction Model

Fig. 3.4 demonstrates the architectural diagram of the ANN Algorithm. It encompasses in total three layers i.e. input layer, a hidden layer, and an output layer. In the input layer, the number of processing elements is equal to the number of input variables that are required to predict the output. In the output layer, it consists of the desired variables to be predicted. The hidden layer is the connection between the given input and the desired output. Based on the complexity of the problem, the number of hidden neurons between input and output layers is decided by the trial and error approach. In ANN, Neurons of the network are structured into the following layers: input, hidden, and output layers.

1. **Input Layer:** This layer provides input to the neural network such as bus route, trips, and its corresponding metadata. The bus route consists of its name, id, and agency name. The bus trip is characterized by shape coordinates, trip id, route id, and direction. The first and last bus stop of each route is the source and destination stop, respectively. The input layer interacts with the data provided, accepts data in the form of signals or features. These features are then normalized to achieve better numerical precision when a mathematical model is applied at the hidden layer [153]. The number of neurons at the input layer is equivalent to the number of features to be considered in the input dataset, in this case, the number of independent variables that affect arrival time. At this stage, small random values are initialized to the weights. The input layer just passes on the information to the hidden layer after adding weights without any computation. It is represented in Eq. 3.5:

$$X_i = \theta(X_1, X_2, ...X_n) \tag{3.5}$$

2. **Hidden Layer:** This layer accepts all the information from the input layer and feed-forward to all hidden layers to process it and forward it to the output layer. Next, this layer extracts all the features from the input layer and performs processing or training of the network. Any network can have one or many hidden

layers. The layers are made up of several interconnected nodes that contain an activation function. The main motive of the activation function is to add nonlinearity into the network. It decides a nonlinear relationship between inputs and outputs of a node and a network. There are many activation functions such as sigmoid, logistic, and hyperbolic tangent functions (tanh), Relu, are the most common choices. This is important because most raw data formats are nonlinear, and we want neurons to learn these nonlinear representations. Hence, in this study, the Relu function is used to scale inputs and targets to $(0, x)$. This function is given by Eq. 3.6:

$$f(\theta) = max(o, \theta) \tag{3.6}$$

Here, the function outputs zero when the result of linear combinations of inputs is less than zero, or else equal to the result.

3. **Output layer:** The output layer consists of results generated from previous layers. It updates errors as well as the weights associated with the connections (edges). The number of neurons in this layer corresponds to the output values of the problem. The neuron with n inputs calculates its output as shown in Eq. 3.7. Patterns are presented to the network via the input layer, which communicates to one or more hidden layers where the actual processing is done via a system of weighted connections. In the output layer, it consists of the desired variables to be predicted.

$$a = f(\sum_{i=1}^{n} W_i X_i + b) \tag{3.7}$$

Where X_i is the i^{th} input, W_i is the value of i^{th} weight, b is the bias and f is an activation function.

4. **Training, Testing, and Validation:** Although, the basic procedure of training any Neural network is the same, however, the accuracy of the result is greatly

dependent upon the type of input/output combinations. Therefore, it is highly important to validate a network to verify that training accuracy is sufficient or more iterations are required. During the ANN training algorithm, we separate data input into two categories: one part is used to construct the model and the other part is used to validate the model. As such, there is not any predefined procedure for categorizing these raw data for validation, several factors such as data type and size of available data should be taken into consideration. Next, we sort this input data to feedforward to the input layer, the first 70% of data can be considered as training data to construct the model and the next 30% is used for testing and validation.

3.4 Case Study: Auckland Public Transport Network

We will use the Auckland city public transportation system as an example to validate our proposed system. Auckland public transport data consist of all the vehicles such as buses, trains, and ferries. We are going to consider the Auckland transport overlay network to utilize it as an alternative communication channel with existing infrastructure. All these buses have fixed routes along with all the scheduled stops. Moreover, the arrival/departure time at each stop is usually strictly followed by a scheduled timetable including the frequency of services. For each route, the frequency of services changes might be for different hours of a day. For example, in peak hours, the frequency of services might be 5 minutes and in off-peak hours, it can be 15 minutes. We will further explore these datasets to utilize them efficiently in our next section.

3.4.1 Dataset Exploration and Their Sources

Auckland Transport data set contains agency name and schedule of busses as well as their routes and the location and number of traversed bus stops. Hence, it allows us to study the spatial-temporal characteristics of the bus system to be utilized for data transmission. To use public transport as another communication network, we assume all busses to be equipped with an IEEE 802.11 module with a capacity of 100 GB storage. Moreover, we also evaluate the case of bus stops being equipped with IEEE 802.11 modules. These bus stops will be considered as parking/offloading spots.

AT includes buses, trains, and ferries as public transport services as shown in Fig. 3.5. This map clearly shows Auckland bus routes. In our work, we will analyze the Auckland public transport bus data only. All these public buses have fixed routes along with all the scheduled stops. Moreover, the arrival/departure time at each stop is usually strictly followed by a scheduled timetable including the frequency of services. For each route, the frequency of services changes might be for different hours of a day, e.g. In Peak hours, the frequency of services might be 5 minutes and in off-peak hours, it can be 15 minutes. Even though the timetable is scheduled for routine operation of public transport, some unpredicted disturbance can cause a delay in arrival/departure times. These unpredicted disturbances may be like traffic congestion, accident, vehicle damage or road work, etc. We are going to consider the Auckland bus service routine operation to utilize it as an alternative communication channel.

We collected Auckland transport datasets from “Auckland Transport Open GIS Data” resources, which contain all the data resources such as bus, train, ferry, traffic mooring, freight network, etc. The arrival times of each coming bus can be seen at displays at bus stops and on the Auckland Transport website.AT dataset is freely downloadable in General Transit Feed Specification (GTFS) format. This dataset not only consists of transportation schedules but also associated geographic information as well.

- **Bus Route:** There are 498 bus services in total which cover 5474 bus stops. The total area covered by the Auckland metropolitan bus routes is 1086 km2. All the bus services cover most residential, commercial, industrial, and educational

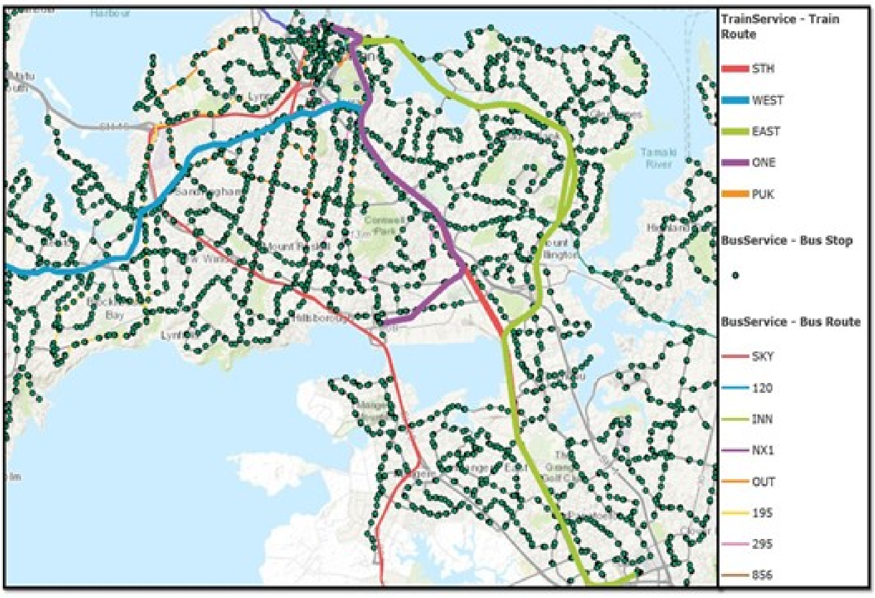

Figure 3.5: Auckland Public Transport Overlay Network

locations in all suburbs. Auckland bus route datasets have been acquired from https://opendata.arcgis.com/datasets, which consist of given attributes.

$< OBJECTID, ROUTEPATTERN, AGENCYNAME,$

$ROUTENAME, ROUTENUMBER, MODE, SHAPELENGTH >$

- **Bus Stop:** Auckland Transport Bus services are operated day and night 7 days a week and almost covers 5474 bus stops. Bus stop datasets contain the following attributes:

$< X, Y, OBJECTID, STOPID, STOPCODE, STOPNAME,$

$STOPDESC, LOCATIONTYPE, STOPLAT, STOPLON,$

$PARENTSTATION, MODE >$

There are four Link services, all run from early morning to late evening, 7 days of the week. These Link services are named City Link, InnerLink, OuterLink, and TamakiLink. All Link services go both loop way and link Auckland other suburbs to main central. City Link only moves in Auckland central. InnerLink

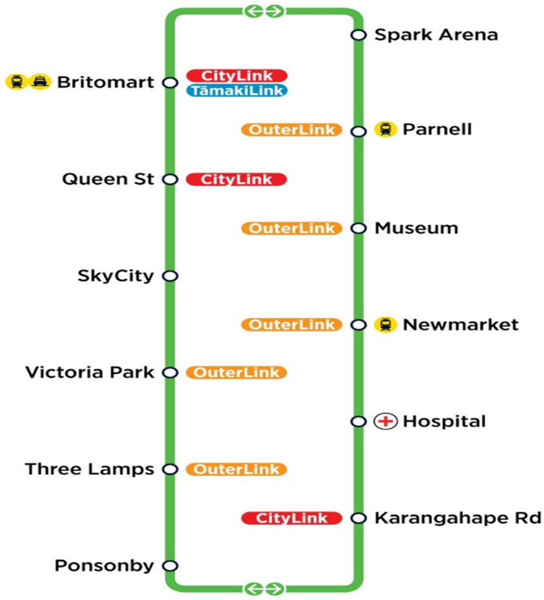

Figure 3.6: Link Services Operated by AT

is green in color and the route starts from Britomart to Parnell, Newmarket, Karangahape Road, Ponsonby Road, Victoria Park, Britomart. OuterLink covers nearby suburbs and starts its journey from Wellesley street and moves from Parnell to Newmarket, Mount Eden, Mount Albert, Westmere, Herne Bay, and then Wellesley Street.

There are four types of bus services in Auckland that connect all parts of the city and they include local services, connector services, peak services, and frequent services. Local services operate within the local central area. Peak Services move only in peak hours. Connector services connect central Auckland to nearby suburbs. Frequent services run every 15 minutes for all 7 days a week. We can use these bus services by analyzing their route and stops in between to carry data all over Auckland. We consider this road network as an alternative communication channel along with the traditional network to reduce the network traffic and utilizing the existing infrastructure to make communication easier and delay-tolerant.

3.4.2 Data Pre-Processing of Collected Dataset

The obtained dataset includes all the information related to buses and bus stops. It comprises the trip id of a bus, timestamp, longitude, or latitude of all the bus stops, etc. This data includes trips over different routes with different directions either upstream or downstream. We have datasets of all bus trips in Comma-Separated Values $(.CSV)$ file and with the help of Sequential Query Language (SQL), this data is then loaded in a database table. The trips, $stop\_time$, and routes datasets are the baseline dataset for the analysis to get details like scheduled arrival time & departure time of all buses bus, fixed latitude & longitude positions of bus stops which in turn helps to compute different data features for bus arrival time prediction.

- **Calculating The Distance Between Two Bus-Stops**

  To evaluate bus arrival time, this is important to know the travel time and distance between two consecutive bus stops. There are a lot of calculation techniques available for calculating the distance between two bus stops. As defined in the description of the data set, the bus stop file contains its stop id along with longitude and latitude attributes. We will be using the well-known distance computation Haversine formula [154] to calculate distance as below:

$$D = 2r \arcsin\left(\sqrt{Havrsine}(\phi_2 - \phi_1 + \cos\phi_1 \cos\phi_2 Haversine(\lambda_2 - \lambda_1)\right) \tag{3.8}$$

  Where D is the distance to be calculated, r is the radius of the earth, which is 6378.1 km, and ϕ_1, ϕ_2 implies the latitude of stop1 and stop 2. λ_1,λ_2 resembles the longitude of stop 1 and stop 2.

  This will help to identify bus stops in the extracted trip of all bus data and keep track of all the bus trajectories. This has been done with the assumption that the time taken to reach one bus stop to another includes dwell time. All calculations will be proceeded with the actual bus service stops sequence.

- **Calculating Bus Travel Time Between Two Bus Service Stops**

  Bus travel time is another feature to be calculated to help us with our bus arrival time prediction. An array of timestamp values is obtained from all the bus stops spots. Eventually, this feature from the stop time file will help to compute travel time between consecutive bus stops and cumulative time taken at each bus stop. The time value in this array is in the format of "HH:MM: SS", so this array will be converted into seconds by the given formula.

$$Time(s) = HH \times 3600 + MM \times 60 + SS. \tag{3.9}$$

  The array will be revised with these calculated times in seconds for each consecutive bus stop. To calculate the bus travel time for the current bus stop, the current time is subtracted from the next time. In some cases, the bus starting from the main bus stop(source) starts with some delay, this may be because of passengers boarding and delay in completing the existing trip. It was also seen that some buses start $1 \sim 2$ minutes ahead of the scheduled time from the source.

- **Calculating Speed Between Two Bus Service Stops**

  Speed is another feature to extract to know the whole day journey of a route. It is being calculated distance covered per unit of time. However, we will be concerned about the average speed over the linkages between all the bus stops of a bus route. With the extraction of this feature, we could calculate the delay in seconds that the bus is arriving early or late on a bus route. The negative

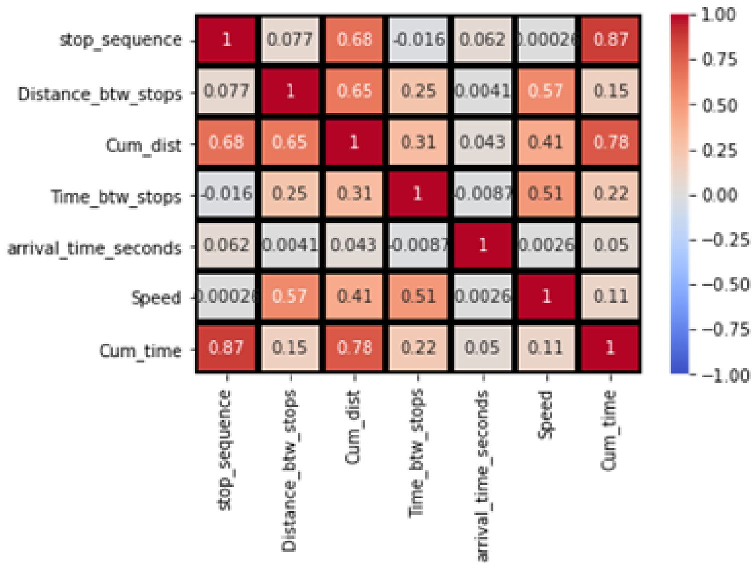

Figure 3.7: Correlation Matrix with Feature Selection

value of delay implies that the bus is arriving late at a bus stop instead of the actual time and the early arrival of the bus is being denoted by the positive value. Correlation matrix helps to understand the relationship between multiple features and attributes in the dataset to train our model. The correlation score value varies between 0 and 1 as shown in Fig. 3.7, If there is a strong and perfect positive correlation, then the result is represented by a correlation score value of 0.9 or 1 or otherwise less.

- **Testing and Validation** To test and validate our ANN model on AT network, we are using 3 months of data from 20 April to 20 June. The collected data were converted to 1410 route segment with 1048574 trips in their operational times for each bus running along the route upstream and downstream. The total bus stops are 18423 to be considered for RSU deployment. The AT training sample data is shown below in Fig 3.8. This is the ready data set to be used for testing and validation after applying pre-processing functions, removing unwanted data

	arrival_time	departure_time	stop_id	stop_sequence	stop_lat	stop_lon	stop_name	stop_code
0	5:20:00 PM	5:20:00 PM	7344-20200424112254_v89.64	1	-36.85009	174.85780	Stop B St Heliers	7344
1	5:21:06 PM	5:21:06 PM	7346-20200424112254_v89.64	2	-36.85029	174.86256	36 Vale Rd	7346
2	5:22:00 PM	5:22:00 PM	7348-20200424112254_v89.64	3	-36.85173	174.86545	22 Bay Rd	7348
3	5:23:43 PM	5:23:43 PM	7391-20200424112254_v89.64	4	-36.85554	174.86560	2 Chesterfield Ave	7391
4	5:24:13 PM	5:24:13 PM	7389-20200424112254_v89.64	5	-36.85653	174.86732	Chesterfield Ave near Kesteven Ave	7389
...	...	...	...	...	...	...	...	...
1048570	2:11:40 PM	2:11:40 PM	8913-20200424112254_v89.64	8	-36.91863	174.72057	107 White Swan Rd	8913
1048571	2:12:10 PM	2:12:10 PM	8915-20200424112254_v89.64	9	-36.91756	174.72162	93 White Swan Rd	8915
1048572	2:13:08 PM	2:13:08 PM	8917-20200424112254_v89.64	10	-36.91547	174.72382	59 White Swan Rd	8917
1048573	2:13:49 PM	2:13:49 PM	8919-20200424112254_v89.64	11	-36.91416	174.72561	Opp 32 White Swan Rd	8919
1048574	2:14:28 PM	2:14:28 PM	8921-20200424112254_v89.64	12	-36.91296	174.72726	3 White Swan Rd	8921

Figure 3.8: Auckland Transport Sample Data for Testing and Validation

and null value. It is known as GTFS static and includes all the bus schedules and associated geographic information. This dataset is static and does not consider dwell time, passenger boarding, alighting and other parameters. We will be using the first 70% as training data to construct the model and the next 30% is used for testing and validation. We will be using a maximum 500 number of iterations for our model. This division has been used by many researchers [155] and helps to have better prediction results and minimum mean absolute percentage error(MAPE)

3.5 Numerical Studies

To validate our idea, we used the Auckland Public Transport as an overlay network with a physical network. We will be evaluating further to support our key findings. Our numerical studies section is about PTDD design based upon static aggregated graph analysis.

3.5.1 PTDD Design Based Upon SAG Analysis

In this section, we represent Static Aggregated Graphs (SAG) analysis [156] by aggregating information from the time-varying bus system and producing a single static aggregated graph to analyze information about contacts between bus and bus-stop, stay time, arrival time and also the frequency for PTDD design. PTDD consists of public transport as another overlay network with an existing physical network for delay-tolerant data transmission. We are performing SAG analysis on a 24-hour time window of the Auckland transport overlay network for capacity analysis. All of the buses have fixed routes and move in directional manner from one stop to another. In this way, the time-varying information and bus storage along with data volume is aggregated into bus capacities for each edge (bus link) in the graph. For example, constructing SAG graphs for different times of the day demonstrates the variation in the bus service over a week. The SAG encoding helps to determine the bus movement all over the city as per their timetable. We use publicly available datasets to characterize the road network. These datasets feature bus line information, bus route, stop number in terms of bus mobility patterns on a road segment in both directions moving all around Auckland. To validate our idea, we used the Auckland Public Transport Case study. We will be evaluating further to support our key findings. Our numerical studies section is divided into three sections.

- Capacity Analysis: Firstly, we will be using SAG analysis to analyze the capacity of the public transport network that how much data can be carried by scheduled buses.

- DTI Impact on Capacity: As we are using buses to accommodate delay tolerant data, Therefore, we will analyze the impact of the Delay-Tolerant Indicator (DTI) on the capacity of the Auckland Public Transport network.

- Bus Arrival Time Prediction: Understand and analyze the obtained results to identify the difference between scheduled and predicted arrival time to estimate the accuracy to utilize public buses for data dissemination.

  In the next section, we will be applying the Auckland Public Transport dataset for more evaluation of these metrics.

3.5.2 PTDD Capacity Analysis

To analyze the capacity of a transport network, it is important to know first the density of vehicles. We have got all the information related to bus routes and bus stops to analyze, which bus can be utilized to disseminate data to all the surrounding places. All these services are well managed by Auckland Transport and operate in both directions. We analyze the movement of buses and the location of the bus stop for the effective operation of data offloading. We assume that this process starts when the bus stops at any bus stop or comes in the communication range denoted R of any bus stop. We will be using a map-matching algorithm [157] to match the bus mobility timestamp on the route. This helps to know the exact time and patterns of the buses moving between sources and destinations. There are in total of 498 bus services which cover 5474 bus stops. Fig. 3.9 gives an overview of all the active buses during the weekdays and the routes covered within respective times. These timings are the regular service periods for most of the bus lines and provide an overview of Auckland Public Transport active buses as per different timings of the day. In addition to that, these active buses cover all the suburbs named as route number.

Fig. 3.10 illustrates the services that run-in all-over Auckland. These services are categorized into four different services such as local services, connector services, peak services, and frequent services. It is clearly shown that among four of these services, there are a maximum number of connector services, which connects different suburbs of

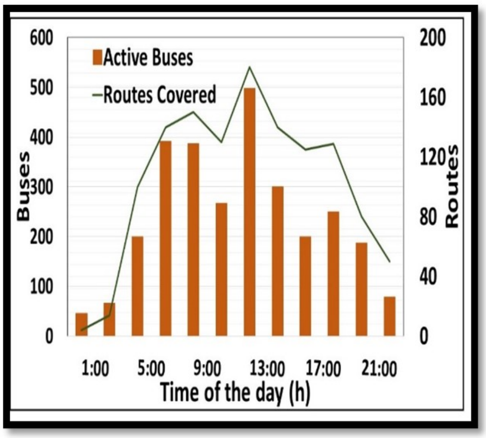

Figure 3.9: SAG for Number of Active Buses and Routes Covered

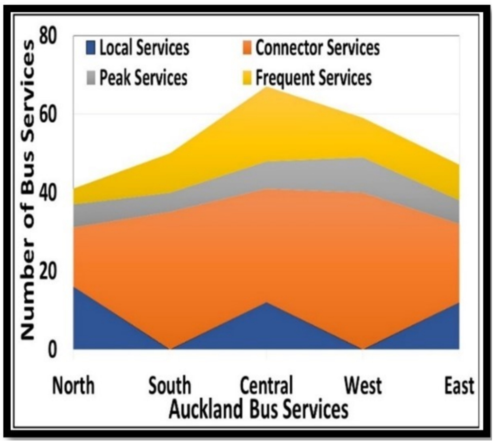

Figure 3.10: SAG for Auckland Bus Services Type

Auckland and has great potential to carry data. These services run every 15 minutes and have a predefined route to move around different areas of Auckland. In such a way if the source location is in West Auckland and the destination location is South Auckland. These services can connect both areas and can carry data to another place.

Bus Service Variation for a Different Region

As discussed earlier, we are using the Auckland Public Transport System datasets. Firstly, we will discuss all areas of Auckland and find out the bus mobility patterns and their connectivity services. Then, we will accommodate the user's needs as per their demands in the next section.

- **The Spatial-temporal Coverage of Auckland Central Bus Services:** Auckland Central will be the hub of Auckland transport to run all the future bus services. We consider Auckland central as a source and forwards data through buses in all four different areas: north, south, east, and west. We start exploring all the bus services first from Auckland central. As described before, all Auckland bus services have been categorized into four different services such as local services, connector services, peak services, and frequent services. In Auckland central, 12 local services operate central Auckland. Next, 29 connector services, which are connected in all directions of Auckland. These services operate at least every 30 minutes, 7 am – 7 pm, 7 days a week. Peak services are operated only in peak hours on weekdays like morning and afternoon peaks and there are 7 of them. Frequent services operate every 15 minutes 7 am – 7 pm, 7 days a week.

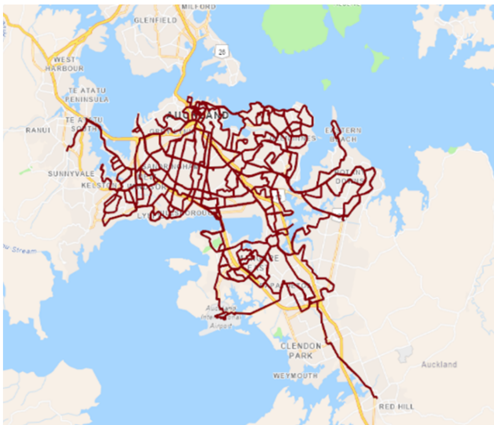

Figure 3.11: Auckland Central Bus Services

Figure 3.12: Auckland Northern Bus Services

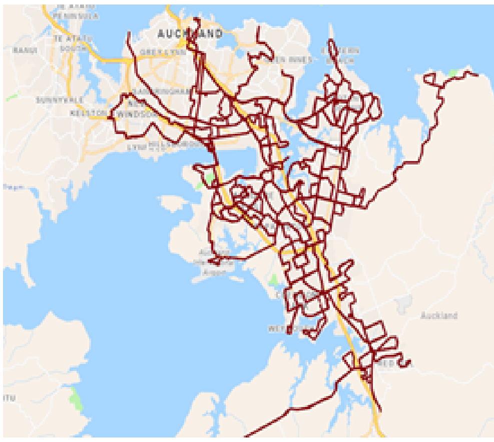

Figure 3.13: Auckland Southern Bus Services

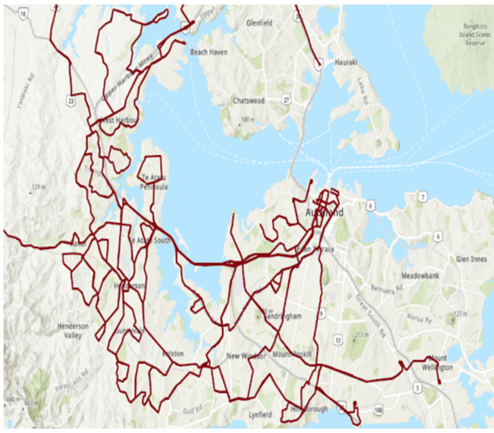

Figure 3.14: Auckland Western Bus Services

* **The Spatial-temporal Coverage of Auckland Northern Bus Services:** Auckland Northern Bus services cover all over north and connect to Auckland central and Auckland west with their connector services as shown in Fig. 3.11, 3.12 and 3.13. There are 8 stations are the main bus stops where buses depart and finish

their journey. Auckland Northern Services has been categorized into five types of services the same as Auckland central including Busway Services. Busway Services forms the backbone for public transport services on the North Shore. The busway runs faster on the motorway, resulting in an opportunity to avoid congestion during morning and evening peak periods. These bus services are 3 in total e.g. NX1, NX2, and 866. All of these busway services connect Auckland central to Auckland north via different routes and stops. In addition to that, there are 4 frequent services, 25 local services, 19 connector services, and 6 peak services. Operating hours are the same as described for Auckland central for all types of services.

⋆ **The Spatial-Temporal Coverage of Auckland Southern Bus Services:** South Auckland covers a huge area of Auckland. The main interchange bus station includes Botany town center, Manukau, Manurewa, Onehunga, Otahuhu, Otara, Papakura, and Pukekohe. Some of these stations also have train services and the last stop for the train is Papakura Train station. From Papakura train station to move further, there are local and connector services which operate every 30 minutes all 7 days. In total, there are 17 local services, 17 connector services, 5 peak services, and 10 frequent services, which operate all over South Auckland.

⋆ **The Spatial-Temporal Patterns of Auckland Western Bus Services:** West Auckland is also a vast area and operates ferry and train services as well including bus services. In west Auckland, Henderson, Westgate, Avondale, and New Lynn are the main bus stops for bus services to operate all over West Auckland. There are 9 peak services, 10 frequent services, and 40 connector services. The connector services usually operate every 30 minutes 7 days a week and connect all nearby suburbs. However, these connector services are further distributed into three categories which are 28 in number and operate every 30 minutes, 8 bus services every 60 minutes, and 4 bus services every 2 hours. There are no local services to operate.

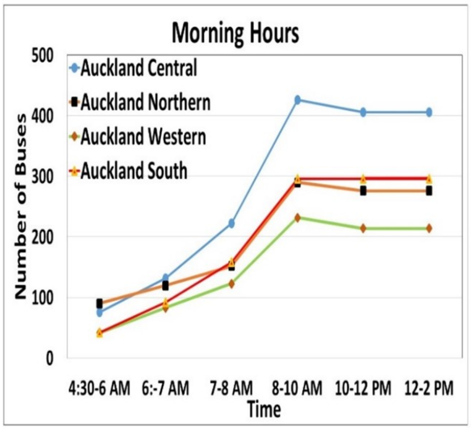

Figure 3.15: Public Vehicle/Bus Density in Morning Hours

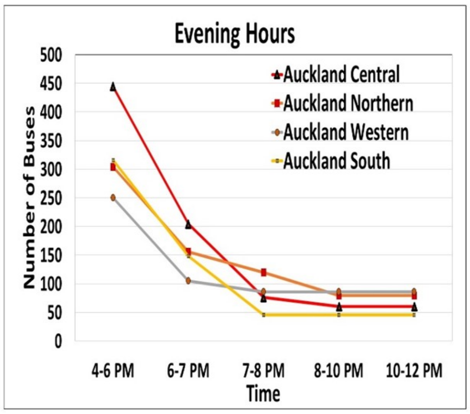

Figure 3.16: Public Vehicle/Bus Density in Evening Hours

As shown in Fig. 3.15, we can see the number of buses operated during the morning to noon hours. For all the areas, there is an increment in buses as time increases. During the peak hours (7-9 am, 4-6 pm), it is more heading towards Auckland central due to people's workplaces. Moreover, everyone starts the working day at 9 am which surge internet traffic and remains consistent until 3 pm. After that, there is a peak in usage until late evening just because school finishes. Therefore, buses can be utilized for data dissemination to alleviate the congestion in bandwidth. Auckland central has more connector buses and connects all surrounding suburbs. As such, before people reach home, they can have their data efficiently. Telecom operators have analyzed the people's habit of data usage, which shows that on an average day, data usage at its lowest at 5 am and begins to rise between 6 am and 8:30 am. Usage remains consistent during the day and jumps upward sharply from 3:30 pm. Same way, if we look at the pattern, it's a decreasing trend from peak hours towards nighttime as shown in Fig. 3.16. These are the peak hours timing of public transport buses and have more express buses to use as well.

Auckland Transport Capacity Analysis

Our main aim was to effectively utilize the existing public transport for data dissemination. For this evaluation, we count all the possible routes of road network from sources to destinations. This study shows the benefits of using buses to carry data. Here we assume all buses are equipped with the same storage capacity of 100 GB. To begin with, we will first study the potential transmission capacity of four different regions of Auckland for one day during weekdays. We are considering all bus services which start from 4.30 am including frequent services, local services, busway services, and connector services. Moreover, we have inbound and outbound services for a route but with different bus stops.

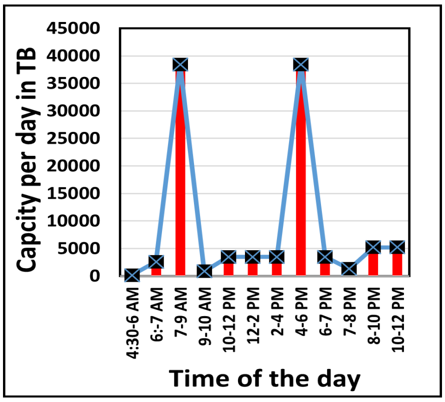

Figure 3.17: Capacity Analysis North Auckland

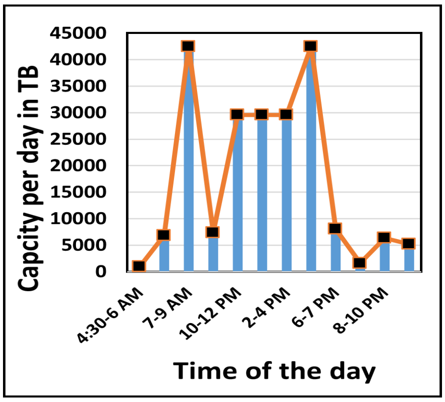

Figure 3.18: Capacity Analysis Central Auckland

As we all know that in every country, the number of bus services is very less in the early morning with the start time at 5 am or 5.20 am with less frequency. There are some bus services such as, whose frequency is 60 minutes during the day. The frequency is an important factor impacting the data capacity for that time of day. We can imagine the increasing trend between 7-9 am and 4-6 pm due to peak/school hours of the bus service with additional bus services during any weekday day. To begin with Northern

Auckland, there are a total of 620 bus services/day. To categorize further, some bus services run only during peak periods including other services. Moreover, the frequency of all routine day services also varies during peak period, any bus which runs every 30 minutes during the day that goes every 5-8 minutes during peak periods. The overall capacity of all buses/day of north Auckland is 106031.8 TB as shown in Fig. 3.17. It is a great number to utilize this road communication network for data dissemination. For example, a central server in a smart city can accumulate data generated from delay-tolerant applications through different wireless sensors all over the city. PTDD utilizes the bus capacity with DTN features to gather and deliver to another nearby data center to reach a specific destination. As said before, Auckland central is the hub of the Auckland

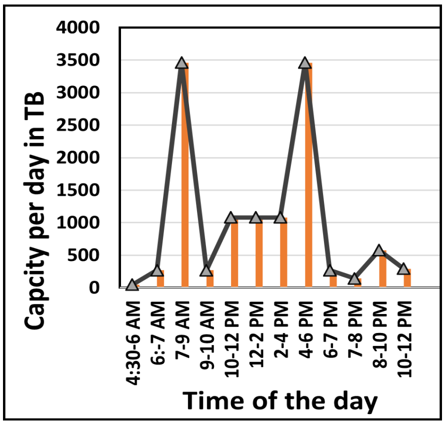

Figure 3.19: Capacity Analysis West Auckland

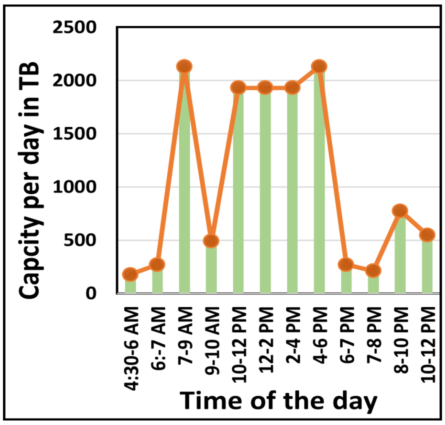

Figure 3.20: Capacity Analysis South Auckland

region. The bus services start from Auckland CBD and go in all directions. However, 544 extra bus services run during the afternoon only. These numbers drop down to 284 during 6-7 pm. In such a way, Auckland's central area has more capacity to disseminate data. The average capacity of Auckland central per day is 210226.8 TB as shown in Fig. 3.18. Same way as in South and West Auckland, there are in total 107 bus services, which runs all over the day. The most interesting thing here is the capacity of the west and south Auckland is less in comparison with central and north due to the train service operated in these two areas, which starts from Auckland central and covers central to the south with many suburbs. In peak hours, the number of bus services reaches 186 and has a capacity of 3459.6 TB in west Auckland as shown in Fig. 3.19. As per Fig. 3.20, the overall capacity of all buses per day of south Auckland is 12037.2 TB.

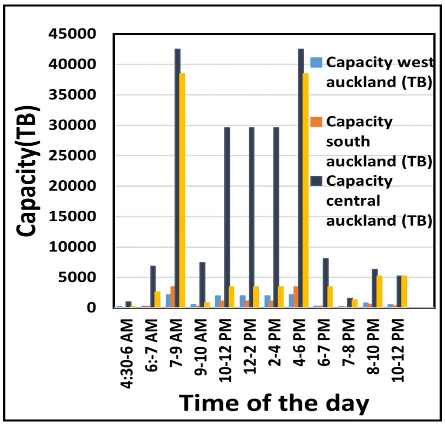

Figure 3.21: Capacity analysis of All Areas Auckland

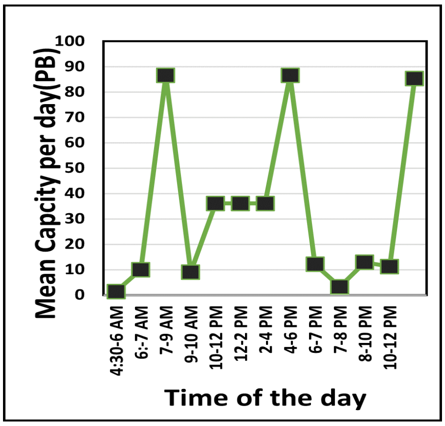

Figure 3.22: The Mean Capacity Per Day

However, in west Auckland, train services are very frequent, and in the future, train services can also be efficiently used for data dissemination and provides add-on functionality to the bus network. As shown in Fig. 3.21. below, for the four regions of Auckland, the north and central Auckland have more capacity in comparison with South and West Auckland to disseminate data all over Auckland. However, the least capacity is 160 TB, which is north Auckland bus services during morning hours 4.30-6 am and the maximum capacity is 42510.4 TB, which is during peak hours of Auckland central bus services. This variation in numbers is the frequency of the buses operating as per different timings of the day.

3.5.3 The Impact of Delay Tolerant Indicator (DTI) on AT Capacity

Here we study how the delay-tolerant factor, termed as delay tolerant indicator, impacts our system capacity. Different data demands have different sensitivity on the time, for example, some of the applications such as online gaming, Netflix, prime, video on demand, virtual reality, and voice over IP are delay-sensitive applications and cannot be delayed. However, on the other hand, there are some delay-tolerant applications such as video surveillance, a huge amount of log files and backup data, smart metering, or road degradation pictures, air pollution data, etc. For these kinds of applications, we can select the network from data being accumulated at one data center and based upon individual demands of these data types (sensitive or delay-tolerant) and if delay tolerant, considering their predefined delay-tolerant indicator representing the tolerant time for the delay.

Figure 3.23: Demands Allocation to Three Different Regions

For example, considering the data accumulation process of surveillance video from all regions of Auckland. Data get accumulated at their respective data center and that data further being sent to different data centers for further verification and ticket allocation with the message-ids (M1, M2. . . . Mn) as shown in Fig. 3.23. We will be utilizing PTDD for these demand allocations and looking forward to the different buses as per their destination address and delay-tolerant Indicator. When a bus arrives at a bus stop nearest to that center, data gets uploaded onto it to carry towards the bus stop near the destination data center. We will conduct sensitivity studies on how the DTI impact the transmission capacity of each bus. We assume that these traffic demands have been initiated at 9 am.

As defined in Table. 3.1, we are considering public transport to accommodate the need of all data centers sending data through central towards all the directions of Auckland. We are demonstrating bus mobility patterns and data dissemination techniques through these bus services. Firstly, we differentiate all the demands as per different attributes such as delay tolerant indicator (DTI), data volume, source, and destination as defined in the flow table. We will look for all the available buses as per DTI defined.

Source	**Dest**	**Distance**	**Number of Buses per day**	**Demands**	**Delay Tolerant Indic (Hours)**
Auckland Central	North Auckland	17.9km	2848	M1	3.7,10,14
Auckland Central	West Auckland	16.9km	4458	M2	3.7,10,14
Auckland Central	South Auckland	17.5km	1030	M3	3.7,10,14

Table 3.1: Summary of undertaken research efforts per approach and network level

1. **Auckland Central to North Auckland:** Data Centre 1(DC1) with message-id M1 wants to disseminate data to Albany, north Auckland, which is 17.9 km in distance. There are in total of 2848 bus services that run for the whole day and carry data. We aim to analyze the capacity of this bus network as per different delay deadline hours. We assume that message transmission initiates at 9 am. It can be seen that, if we consider the delay requirements for the data service, such as 3,7,10 and 14 hours, there be limited bus services for these 3 hours as these non-peak hours but more possibility when DTI value extends up to 10 hours and if can be 24 hours, the system can send about near hundred thousand. As shown

in Fig. 3.24, we calculated the capacity of these buses for that one day to different delay-tolerant deadlines.

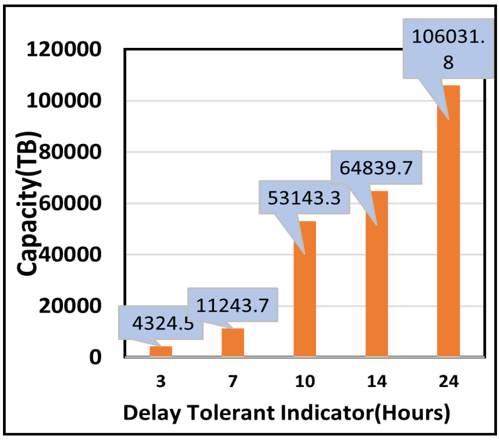

Figure 3.24: Auckland Central to North Auckland(M1)

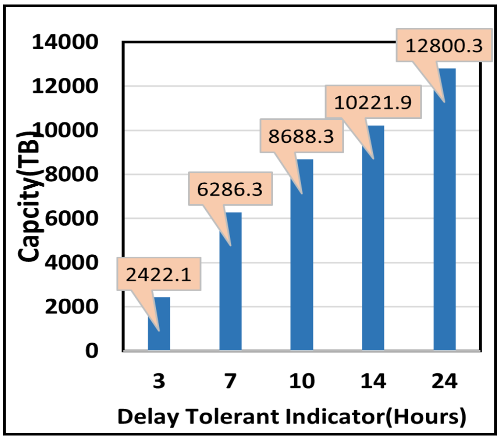

Figure 3.25: Auckland Central to West Auckland(M2)

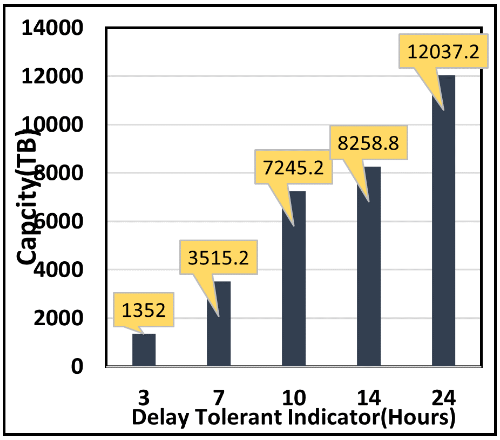

Figure 3.26: Auckland Central to South Auckland(M3)

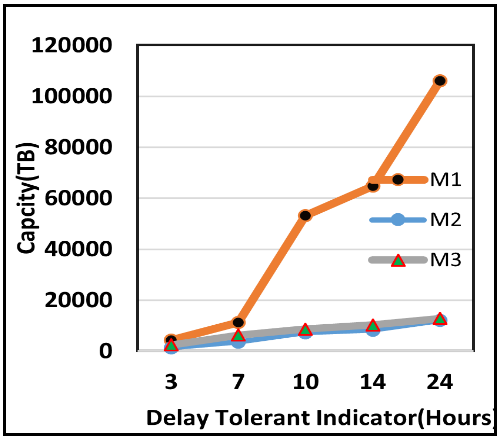

Figure 3.27: Capacity of All Three Demands

2. **Auckland Central to West Auckland:** DC2 with message M2 now has another destination in west Auckland. All the buses go through different routes and different bus stop covering all the region in between. In this case, we differentiate all the bus services with their types. Same as above shown in Fig. 3.25, we assume the DTI deadline as 3,7,10, and 14 hours. In 3 hours, there will be limited services and as we start increasing hours, we have more options available to utilize bus service efficiently.

3. **Auckland Central to South Auckland:** Message M3 has a destination to south Auckland. DC3 wants to disseminate data in South Auckland which is 17.5 km in distance from Auckland central. The whole day capacity of south Auckland is 12037.2 TB. However, as per different DTI values, it varies, and we can avail of some of the buses only as shown in Fig. 3.26. Moreover, Fig. 3.27 shows the capacity of PTDD for all three demands being generated by different data centers and illustrates that DC1 has more potential in comparison with others. However, other DC2 has a minimum capacity of 1352 TB and gradually increases as per rising hours.

   In such a way, we have analyzed the overall capacity of the public transport network, which proves that there is great potential in the public transport network and we can utilize them for data dissemination. However, for accurate modeling of data allocation onto buses, it is mandatory to know the accurate arrival time, dwell time, and leaving time of the buses at each bus stop. Therefore, we will be using bus arrival time prediction model to have a more authentic arrival time to allocate data onto each bus.

3.5.4 Bus Arrival Time Prediction for AT Network

The processing of the ANN model depends upon the dataset generated and filtered as an input. The steps below will be followed by our ANN model to predict bus arrival time. *Step1:* Generating observations of the bus route: As per our Auckland public transport case study, we will consider 3 test trips of the bus route. Bus route: 744,141 and 70. Random observation of all trips with bus stops is to be generated, whose arrival time is to be predicted.

Step 2: Retrieve bus stop location details of all bus routes: Next, following our algorithm, we will fetch all the bus stops concerning their routes. For example, on the bus route, there are a total of 29 bus stops. We will be calculating the bus arrival time for all these bus stops.

Step 3: Generate a Symbolic formula and perform ANN model training: Our ANN model is accepting input as bus stop sequence(BS), the distance between two stops(d), the cumulative distance for the whole test tripCD_{tt}, the time between stops(T_s), arrival time in seconds(AT_s), speed(S), and cumulative travel time(CTT_s). Therefore, the initial symbolic formula description of the model to be fitted will be as.

$$X = (B_s + d_s + CD_{tt} + T_s + AT_s + S + CTT_s)^t \tag{3.10}$$

Here, the function outputs zero when the result of linear combinations of inputs is less than zero, or else equal to the result.

Step 4: Computing prediction and storing the predicted value: In the previous step, when a model is trained with sample data of a fixed route, ANN model results are used to predict bus arrival time for all other routes. These values will be stored in the predicted data frame and will be used for the comparison between actual and predicted arrival time. Similarly, *Step 3* and *Step 4* will be repeated for all the test trips.

Step 5: Performance metrics evaluations: We will consider the following performance metrics to estimate the results from the ANN model for all the predicted and actual arrival time values.

- MAPE (Mean Absolute Percentage Error) = MAPE is defined as the average percentage difference between the observed value and the predicted value of bus arrival time. Where y_i = Predicted value, y_0 = Observed value.

$$MAPE = \frac{1}{n} \sum_{i}^{n} \frac{|y_i - y_0|}{y_0} \times 100\% \tag{3.11}$$

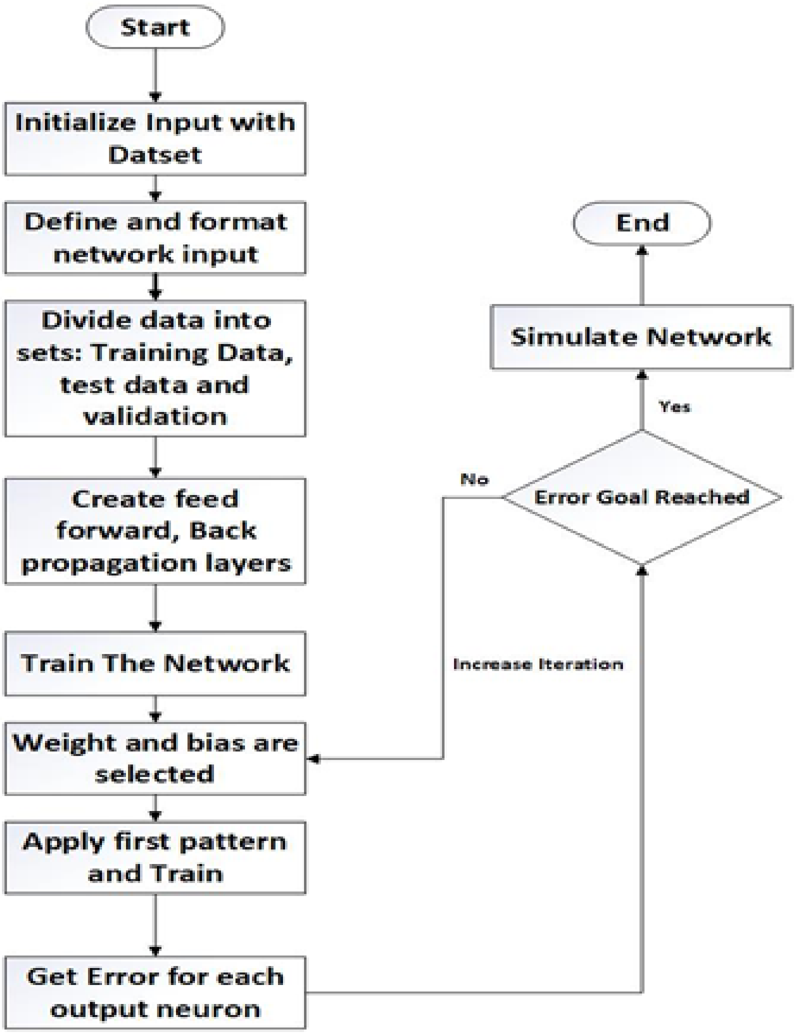

Figure 3.28: Flow chart ANN for Bus Arrival Time Prediction

- SMAPE (Symmetric Mean Absolute Error) = It is an accuracy measure based on percentage (or relative) errors between the observed value and the predicted value.

$$SMAPE = \frac{1}{n}\sum_{i}^{n}\frac{|y_i - y_0|}{|y_i + |y_0|/2} \times 100\% \tag{3.12}$$

3.5.5 Evaluation Results of the ANN model for all test trips

To evaluate our ANN model, three test trips are conducted for different routes of the Auckland public transport network. Table. 3.1 is presented to demonstrate the set of test trips with random bus trips that were created by the algorithm for bus routes 744, 82, and 70. running in the afternoon hours of the day which also implies that the ANN model was trained only on the class 'B' data. With the help of the algorithm presented, the target arrival time of the bus was recognized for each trip at each Bus Stop.

Test Trip	Number of Bus stops
Test Trip 744	29
Test Trip 141	32
Test Trip 70	46

Table 3.2: Set of test trips with the number of bus stops

Algorithm 1: Bus arrival at Bus Stop

Input : B: Arriving Bus, T_{en}: Actual Entering Time, T_{Pr}= Predicted Arrival Time, T_{st}= Stay Time

Output : Status Message.

```
for b ∈ B do
    if b ∈ B_L, d < 3km, T_en = T_Pr then
        settype(m,TRANSFER) ;    // Data assigned to the bus
    else
        Available(T_st,T_Pr) ;    // Check for Bus Stay time and Predicted time
        Delay(s)
        settype(m,TRANSFER)
    end if
end for
return b;
```

ANN model was trained and tested with such random observations, and then MAPE and SMAPE metrics were estimated for actual arrival time and predicted bus arrival time values from the ANN model. As per Algorithm 1 defined below, we can offload data onto buses as per their predicted time.

Figure 3.29: Test Trip 744

Figure 3.30: Test Trip 141

Figure 3.31: Test Trip 70

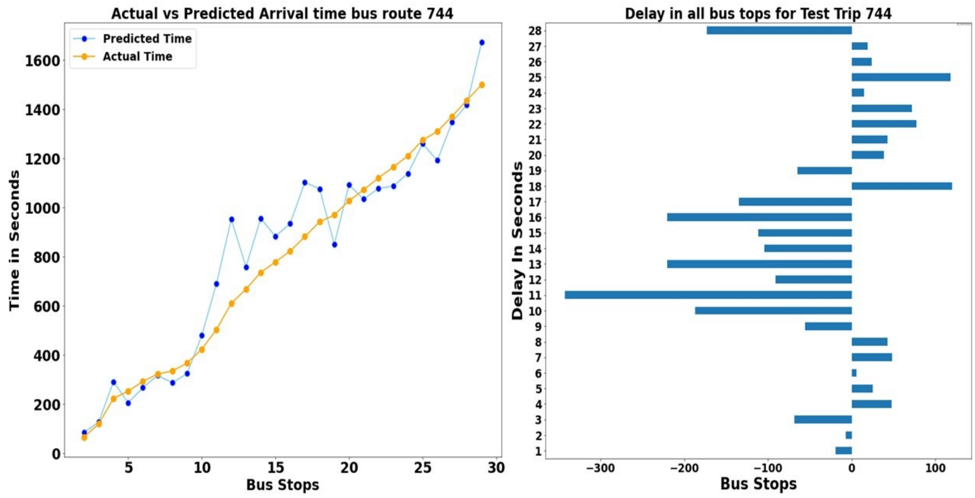

Figure 3.32: Test Trip 744: a)Actual Vs Predicted Arrival Time b) Delay at Each Bus Stop

1. **Test Trip 744:** The testbed selected as a sample is the Auckland Transport Bus route, 744. Which is one of Auckland's central services and connects St Heliers To Panmure Via Glen Innes, considering downstream direction covering 29 stops with trip duration for 25 minutes and length of route as 7 km in between Stop 1 and Stop 29. Figs. 3.29,3.30 and 3.31, are about the map of the bus route (snapshot from the moovit app). and cumulative travel time of the bus to all bus stops of that route. Fig. 3.32(a) illustrates the behaviors of actual and predicted bus arrival time at each bus stop after validation of the neural network algorithm. On the x-axis, the bus stop numbers are plotted, starting from the target station of each testing sample up to the last destination of the bus trip. On the y-axis, the

arrival time(seconds) taken at which a bus reaches any bus stops on its route is plotted. Fig. 3.32(b) represents the delay(seconds) to reach each bus stop. The negative value represents that the bus is arriving late at each bus stop, on the other site, positive values indicate the early arrival of buses at each stop.

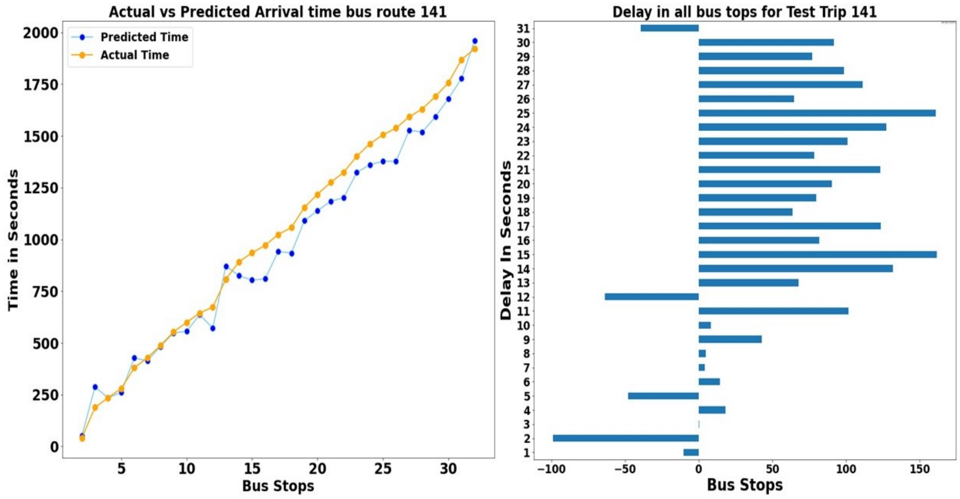

Figure 3.33: Test Trip 141: a)Actual Vs Predicted Arrival Time b) Delay at Each Bus Stop

2. Test Trip 141: The next test trip selected is number 141, which is called Henderson West Loop Anticlockwise. This trip has 32 stops and covers the whole journey in approximately 33 minutes. The bus departs from Stop A Henderson Interchange and finishes at Stop B Henderson Interchange. The operating hours for this bus are from 05:15 to 23:15 every day including weekend hours from 06:38 to 23:08. Same way as the previous trip, Fig. 3.33(a) illustrates that there is variation between precited and actual arrival time. However, another Fig. 3.33(b) clearly shows that the bus is arriving early most of the time at each stop except 5 or 6 bus stops, which clearly states that we can use public transport as another communication mode with delay-tolerant features.

3. Test Trip 70: This test trip 70 starts from 56 Customs St east near Britomart and ends in Stop A Botany town center. This trip covers a total of 46 stops in

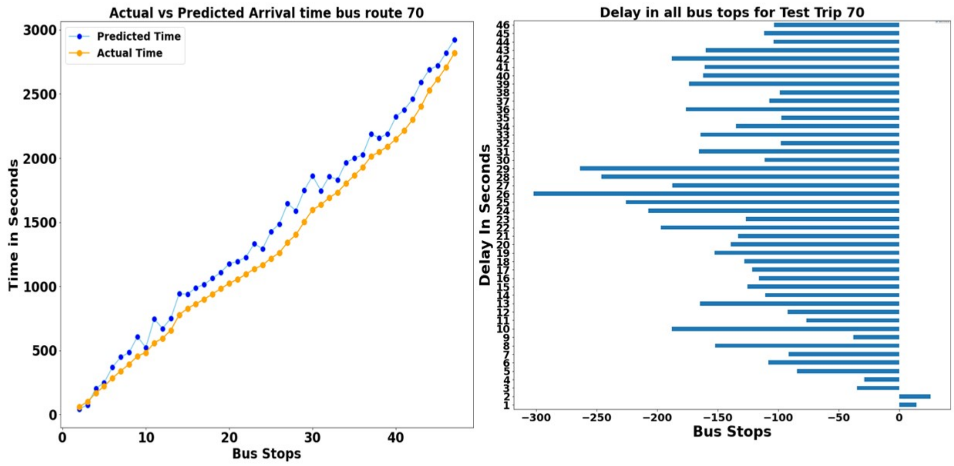

Figure 3.34: Test Trip 70: a)Actual Vs Predicted Arrival Time b) Delay at each bus stop

approximately 58 minutes. This bus route is operational every day and the first journey start at 00:05 and end at 23:50 every weekday and on weekend, it begins at 06:15 am and ends at 23:35. Similarly, Fig. 3.34(a) illustrates the trend of actual and predicted bus arrival time at each bus stop. This route shows that actual and predicted arrival time is different on each bus stop and never on the scheduled time. In Fig. 3.34(b), delay(seconds) represents all the negative values and implies that the bus is late at each bus stop.

MAPE	Interpretation
< 10	Highly accurate forecasting
10-20	Good forecasting
20-50	Reasonable forecasting
> 50	Inaccurate forecasting

Table 3.3: MAPE value and its interpretations

Table 3.3 represented containing typical MAPE interpretation to analyze our ANN model results.

Table 3.4 is created to show the MAPE and SMAPE values calculated for each test

Test Trip	MAPE	SMAPE
Test Trip 744	14.98	0.1447
Test Trip 141	13.34	0.1551
Test Trip 70	19.83	0.0687

Table 3.4: Calculated MAPE and SMAPE error values

trip and the lowest MAPE & SMAPE that were estimated for the model was observed for test case trip 744 with 13.91% and 0.1477 error respectively.

In such a way, we have analysed the actual and predicted arrival time of the bus at each bus stop. Our PTDD system will be allocating data onto each bus when the bus comes in contact of the bus stop. However, the well-known arrival time of the bus helps to improve the performance and offloading efficiency of our PTDD system.

3.6 Summary

In this chapter, we discussed the great potential of public transport to use as an alternative communication channel. For delay tolerant data needs, our approach aims to best utilize the PTDD and their parking spots/bus stops with local storage to offload and upload data. We used Auckland public transport to prove that buses/public vehicles have a huge capacity to utilize them as a data carrier. Computed features like distance traveled, demand characteristics, and time of day, average speed, travel time between bus stops were obtained from the Auckland transport gtfs dataset. Although the available data were limited and historic, some assumptions had to be made for data processing to create input to train our model and some data points had to be ignored because of errors and duplicates in it. Accordingly, a public vehicle going in a suitable direction can carry data along with it and there is no extra fuel consumption while transmission. Based upon these performance metrics, we analyzed the impact of the DTI factor on capacity analysis our ANN model proves that there is a small variation in the actual and predicted arrival time of the bus. We also used an advanced neural network algorithm to predict bus arrival time prediction at each bus stop for each route. The results presented here appear to be reasonable and promising, which ultimately proves that public transport can be used as another alternative communication network for delay-tolerant data needs.

Chapter 4

Software-Defined Connectivity for Network Selection in a Heterogeneous Network

4.1 Introduction

In the previous chapter, we have discussed the capacity of the public transport network to contribute to data communication. We analyzed that there is a huge potential for using Public Transport Assisted Data Delivery System (PTDD) to deliver delay tolerant data traffic. In this chapter, we are proposing a heterogeneous content delivery architecture to make an optimal network selection among different networks. We leverage this public transport and handle it using logical centralization with Software-Defined Connectivity (SDC) for efficient and better management of network selection among different networks. SDC is a paradigm derived from Software Defined Network (SDN), where a central software program, called a connectivity controller dictates the overall network behavior and forwarding strategy as per the demand and objective of each service. The main difference between SDC and SDN connectivity is that SDC works on delay-tolerant behavior and utilizes existing road infrastructure and takes forwarding decisions for energy efficiency. Network devices follow all forwarding rules, while the controller controls all forwarding decisions with a global knowledge of everyone's profile and their requirements. The SDC Architecture consists of all the real objects in the physical things layer to initialize, control, change, and manage network behavior dynamically via open interfaces. Recall from the previous chapter that bus stops temporarily store data and load onto buses as per the routes and destination of the data. The controller takes full charge of making an important decision for network selection as per different attributes of the message. Our main contributions to this chapter are: -

- **Software-Defined Connectivity Architecture (SDCA):** We describe the SDC approach for data dissemination in the heterogeneous network to fulfill the varied requirements of different services. We perform a centralized selection of networks in the control plane of SDCA, the controller takes data forwarding decisions to choose the optimal network interface from the available networks.

- **Multi-Attribute Decision Making (MADM):** - SDC controller uses the MADM technique for network selection among different networks based upon different attributes and criteria. The goal of MADM is either to design the optimal alternative or to choose the best one from the predefined alternatives.

- **Data Allocation onto Buses:** SDC controller is also responsible for allocating data onto buses as per passing stops and stopping stops. The stay time of the bus can help us to determine the offloading capacity at each bus stop.

The remainder of the chapter is structured as follows. In Section 4.2, we present the background of the network selection scheme and their respective methods. The section 4.3 is about SDCA for data dissemination in the heterogeneous network. In Section

4.4, we describe the MADM method for network selection among different alternatives. Section 4.5 illustrates the data allocation model onto buses. Section 4.6 validates all models with performance evaluation Finally, Section 4.7 draws the summary of this chapter.

4.2 Background

Nowadays, the vehicular network is considered a promising network that is available on the road and one of the communication mediums via inter-vehicle or vehicle-to-roadside unit communication. Public transport is one of the vehicular networks with scheduled movement and scheduled routes of public vehicles. Therefore, conventional homogeneous communication, vertical handoff, and data offloading are a few diverse applications [158]. It is very important to consider different attributes to decide on different applications. This is just possible with MADM algorithms for appropriate decisions.

There is a vast literature on MADM based network selection algorithm [159–161] Many of these studies are user-centric and helps to make decisions based on their preferences. Most MADM algorithms for the network selection problem are compensatory algorithms, including AHP, GRA, SAW, MEW, TOPSIS, DIA, and ELECTRE [130]. Many researchers have found out many other types of algorithms to resolve VHO problems and network selection in the heterogeneous network. Some of them are utility functions [162], genetic algorithms [163], and game theory [164]. Utility functions assign values as per the ranking of choices for the user's satisfaction. Abid et al [165] proposed an innovative single-criteria utility function that measures user satisfaction and captures sensitivity for each decision criterion for deciding for handover.

In [166], the researcher proposed a utility-based fuzzy-Analytic Hierarchy Process (AHP) based network selection in heterogeneous wireless networks. They categorized different applications such as voice, video, and best effort and triangular fuzzy numbers were used to represent their comparison matrices. The results obtained prove that the MEW method gives better scores with utility functions. Jian et al [167] proposed a joint multi-criteria utility-based algorithm to assist the vehicle in infrastructure networking for energy efficiency. User's preference for different attributes such as bandwidth, delay, signals intensity, and network cost help to establish utility functions and energy-efficient network selection algorithm. Eventually, some works focused on the energy-efficient multi-connectivity for ultra-dense 5G heterogeneous networks there had also been published [168].

4.3 Software-Defined Connectivity Architecture (SDCA)

In the section, we give a schematic overview of the operations of the infrastructure in charge of offloading large amounts of delay-tolerant data over the road network. We present, Software Defined Connectivity Architecture (SDCA) to leverage the advantage of logical centralization as shown in Fig. 4.1, where a central software program, called a SDC controller takes offloading demands from each service as an input in its local storage and stores data there for a certain time to offload onto a vehicle. This approach consists of an SDC controller, roadside unit centers (RSUCs), roadside units (RSUs), Base Stations, vehicles, and users. Moreover, it also defines connectivity options such as infrastructure-to-infrastructure (I2I) links and vehicle-to-infrastructure (V2I) links.

The SDCA is a network management tool and is composed of a data plane, control plane, and application plane. The foundation of SDCA is a centralized controller that controls the activities related to network management and data forwarding. Some of the key points are highlighted below based on the global view of available network and service requirements of SDCA.

a) The data plane includes all forwarding devices such as BSs, vehicles, and RSUs

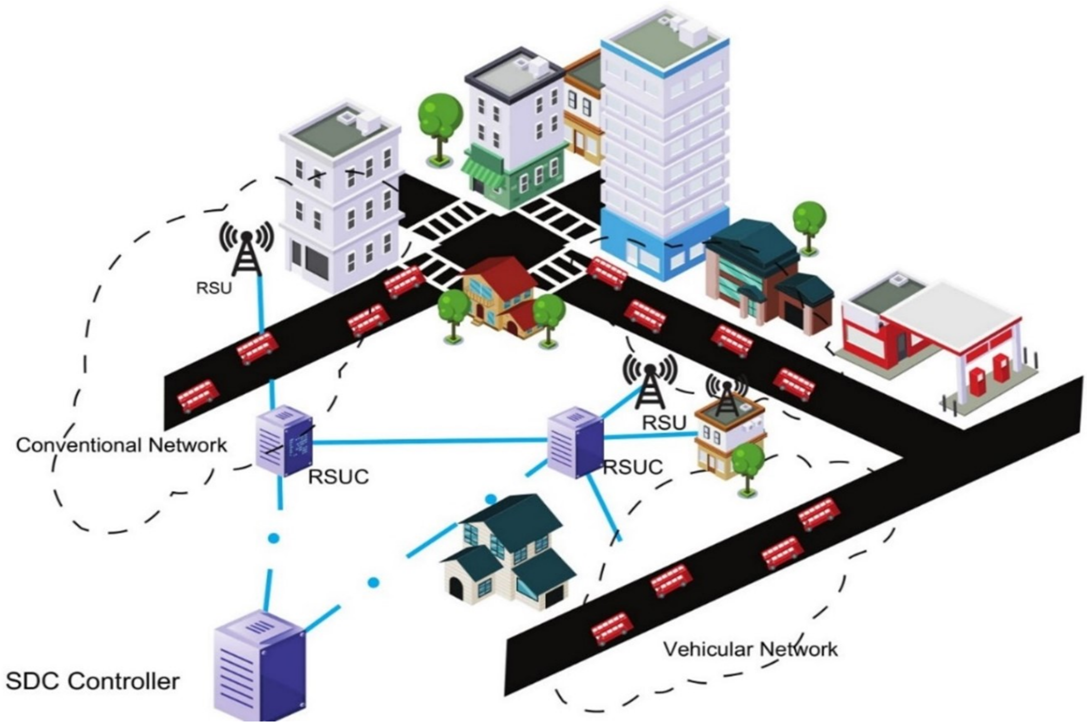

Figure 4.1: Software-Defined Connectivity Architecture (SDCA)

including wired or wireless communication links. The data plane is more focused on the data collection, checking flow table entry, service requirements, services, and then forwarding data into the control plane.

b) The Control plane is controlled by the SDC controller. The controller gathers all necessary information and installs flow table entry in each element of the data plane to take important decisions of network selection based upon different services of each user. In such a way, the controller considerably simplifies the user's requirements and forwards data on a suitable network.

c) The application plane directly faces different application requirements. Therefore, the application plane is mainly responsible for generating rules and strategies. In general, energy efficiency, delivery probability, and delay, all the parameters are considered in a different way as per different services.

Moving further, we will be discussing the details of the whole process of SDCA.

- **SDC Controller:** The controller translates the network policy to actual packet forwarding rules. It makes all traffic forwarding decisions based upon the service requirement as shown in Fig. 4.2. It has many connectivity options to consider for communication. It makes demands of all services to store in the flow table and matches the profile with different parameters such as parking spot, data volume, data type, route, and destination offloading spot. Then, it follows the entry of all vehicles at the parking spot to arrange the pickup of the data. The scheduled movement of all vehicles with installed storage capacity is stored in a geographic database managed by the controller which then will know the fixed-route until destination. Each connectivity component such as RSU or buses has its predefined location.

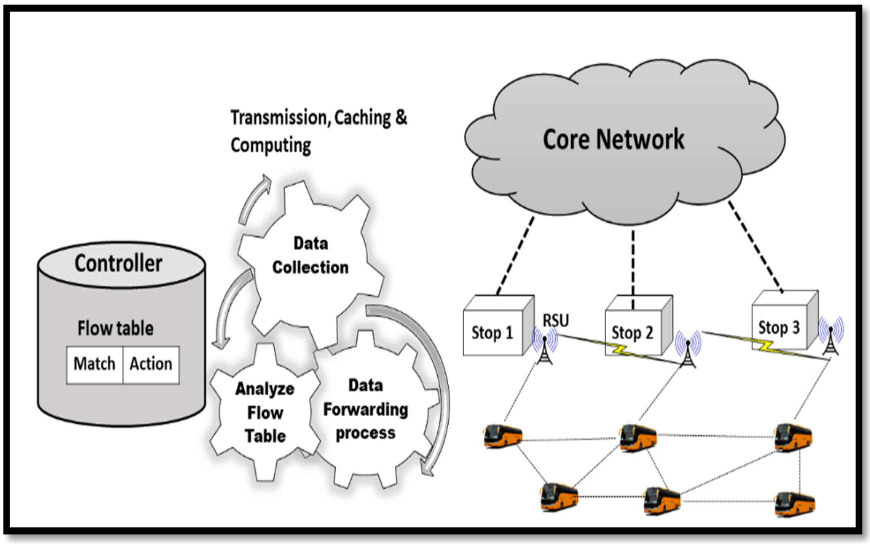

Figure 4.2: Transmission, Caching, and Computing

- **Data Collection:** The data generated from different users and applications get accumulated at the data center near deployed RSU. Every Offloading spot/parking area is equipped with a local storage room or repository, where data is stored until it is transferred to a parked vehicle or until the Internet drop-off or pick-up decision is taken by the SDC controller as per the flow tables' entry. As shown in Fig. 4.3, the controller takes the demands and objectives of each service and stores them in local storage, it analyses its data type and accordingly matches the direction of the passing vehicle against the destination offloading spot. However, if the data type is non-delay tolerant, the controller selects an internet option for the successful delivery of messages.

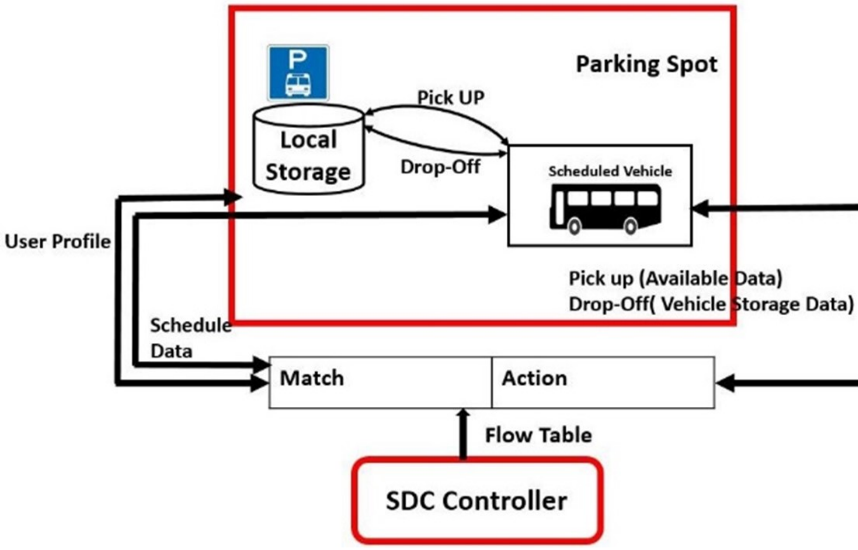

Figure 4.3: Data Collection at Parking Spot/Bus Stop

- **Analyze Flow Table:** The flow table helps the controller in making the forwarding decision as per the profile of each user and their recommended services. The flow table consists of a list of parameters such as the data type, data size, and delay-tolerant indicator (DTI), and distance traveled. They match the data volume and data type as per the possibility of the scheduled vehicle moving in the direction of a destination spot. The flow table 4.1 consists of the flow-id number with all other details needed to act. The controller regularly updates the flow table with new demands and information about completed transfers.

- **Network Selection Forwarding Process:** The forwarding process is the network selection procedure between a traditional network or vehicular network, which depends upon the service type of data. After matching each entry of the flow

Flow ID	Data Size(GB)	Delay Tolerant Indicator(hrs)	Distance(km)
249	500	2	5
276	1000	10	10
676	2000	7	7
267	4000	9	8
432	8000	10	15
254	16000	14	13

Table 4.1: Flow Table to match and action

table, the controller selects a network and forwards the data onto the selected network. Multicriteria Decision Making (MADM) is being used for network selection among all the available networks. The network selection procedure ultimately aims for the best network that can support the required service(s) and avoid excessive switching among different networks to minimize service interruptions and energy consumption.

- **Data Allocation onto Network:** After analyzing all the possible options and network selection, data gets allocated onto any of those networks. As per all application requirements, either data will be allocated onto the internet or vehicular network. Again, the controller is responsible for carrying and updating the global information of the complete network topology and providing a stable route from source to destination. Considering all the requirements and delay factors, data gets allocated either on a traditional network or vehicular network.

4.4 Multi-Attribute Decision Making(MADM)

As defined above in Section 4.3, the controller will take all network selection decision based upon service requirements. We introduce the MADM method used by the controller in response to suitable network selection. This model helps to make forwarding decisions fairly. MADM is an important tool that assists in the solution of complex decision-making problems and analyze network selection problems in a heterogeneous network. There are a few characteristics of MADM given below:

a) Alternatives: Alternatives are defined as several different options to prioritize or select. These can be called candidates, users or networks etc.

b) Decision Matrix: Any MADM problem can be mathematically defined by using a decision matrix, $L(M \times N)$.

$$L = \begin{array}{c} \begin{array}{cccccc} C_1 & C_2 & \cdots & C_j & \cdots & C_N \end{array} \\ \begin{pmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,j} & \cdots & x_{1,N} \\ x_{2,1} & x_{2,2} & \cdots & x_{2,j} & \cdots & x_{2,N} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i,1} & x_{i,2} & \cdots & x_{i,j} & \cdots & x_{i,N} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{M,1} & x_{M,2} & \cdots & x_{M,j} & \cdots & x_{M,N} \end{pmatrix} \end{array} \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_i \\ \vdots \\ A_M \end{array} \tag{4.1}$$

Where $A_1, A_2, A_3, \ldots .A_i, \ldots ., A_M$ denotes all the alternative/parameters to consider for decision making. $C_1, C_2, C_3, \ldots .C_j, \ldots ., C_N$ represents all N criteria, which is being calculated as per different alternatives and denotes its performance. For example, $x_{i,j}$ is the performance ranking of ith alternative w.r.t. j^{th} alternative. The main aim of the decision matrix is to select the best alternative from the given alternatives with respect to others.

c) Attribute Weight: Attribute weight is the value obtained by the decision-maker as per each attribute of the network. This weight depends upon the value assigned to the attribute. This weight is being calculated by the pair-wise comparison matrix.

d) Normalization: The attribute used for network selection have different measurement units. So, normalization is a necessary step for this calculation.

MADM algorithms have high accuracy and low difficulty. They capture different parameters (e.g., QoS, bandwidth, delay, data volume, cost, etc) and select the most suitable network. There are many possible solutions for MADM problems. Popular methods include simple additive weighting (SAW) VIKOR, multiplicative weighting (MEW), gray relational analysis (GRA), TOPSIS, Fuzzy TOPSIS (FT), and AHP. We have provided detailed literature that many researchers have been used MADM techniques for network selection.

In our proposed work, we will be using one of them for the normalization of attributes. provides a detailed description of the whole process of network selection is shown below in Fig. 4.4.

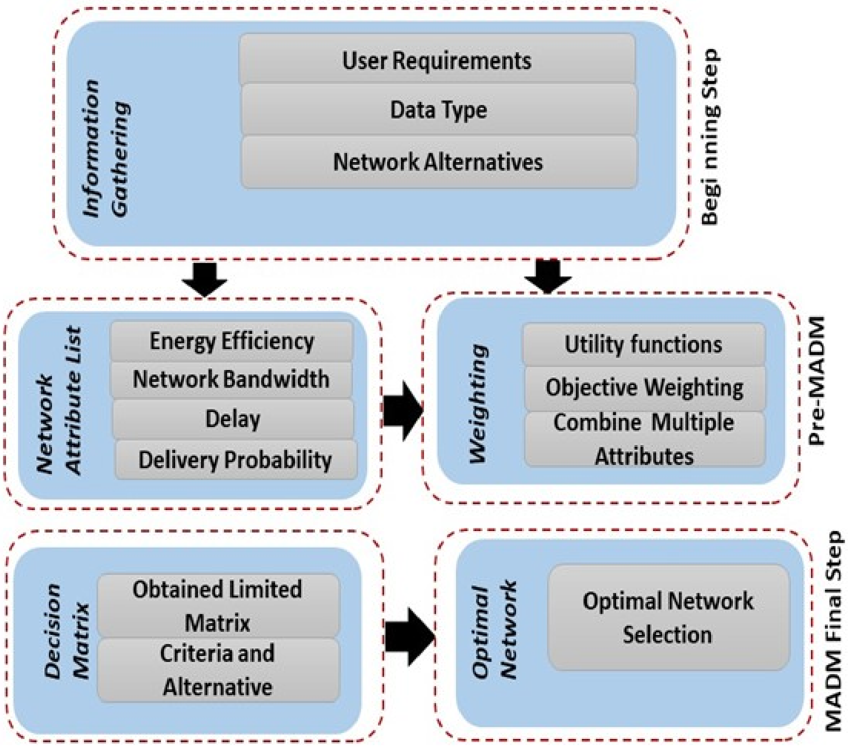

Figure 4.4: MADM for Network Selection

4.4.1 Beginning Step

The beginning step is the first most step of the MADM process, which gathers the required information and triggers the process. In this step, there are the following options to consider.

- **Service's requirement:** The most important aspect is the user's requirement. For different users, they have different demands and object. In our proposed system, we categorize user's requirements into three categories such as Service 1, Service 2, Service 3. All these different services have different sensitivity for the same network attribute. For example: Considering bandwidth as an attribute, if its service 1, lower bandwidth will be used. However, if its a huge data transfer, higher bandwidth will be used. In addition to that, it is assumed that a user can select any one service at one time. Users can select the priority of services used. They can select the urgency of data delivery or non-urgency, which relates to the data type such as delay tolerant or delay-sensitive and helps the controller to take optimal network selection decisions.

- **Data Type:** Data types belong to the type of application selected by users. It can be delay tolerant or delay-sensitive. Some of the services like video or data type can be categorized as a real-time or non-real-time application and accordingly can be delayed for some time. This is another important information to consider for optimal network selection

- **Network Alternatives:** In our proposed work, we are demonstrating to offload data from traditional networks to road networks with delay-tolerant conditions. Therefore, to choose among a list of networks, we will be considering WLAN, UMTS, and Vehicular Network. The controller will choose the best optimal network among these networks based upon user requirements and data type. Three of these networks have different properties. The vehicular network is used for all delay-tolerant applications, such as emails, data backup, video download, and photos, which significantly contribute to energy efficiency without a negative effect on user satisfaction. We assume that all vehicles are equipped with On-board units (OBU) to carry data. If we compare the other two networks; WLAN networks are managed for higher bandwidths and lower delay applications, although, UMTS networks are the most energy-efficient with lower bandwidths requirements and large delay.

Next, considering all the requirements in the process of network selection, we integrate utility theory with the AHP process to design our network selection algorithm as shown below in Fig. 4.5. We consider characteristics of different types of services and their respective weights to define utility functions and the scores of user's preferences by defining rank preference through AHP. Therefore, we are providing a comprehensive structure for users to give their preference and the controller can take decisions based upon their requirements.

4.4.2 Pre-MADM

This step includes preparations before combining all the criteria, including the weighting procedure and attributes adjustment procedure. The left part of this step is more about defining all the attributes to decide optimal network selection. The network attribute list consists of energy efficiency, delay-tolerant value, network bandwidth, and delivery probability. The right part of this step utility values for each attribute, weighing of different attributes to each other and gives the best permutation to analyze optimal network selection. In our proposed method, users decide all the requirements and importance. The controller collects these requirements and proceeds further with the weighing procedure. Based on these parameters, the measurement metrics about

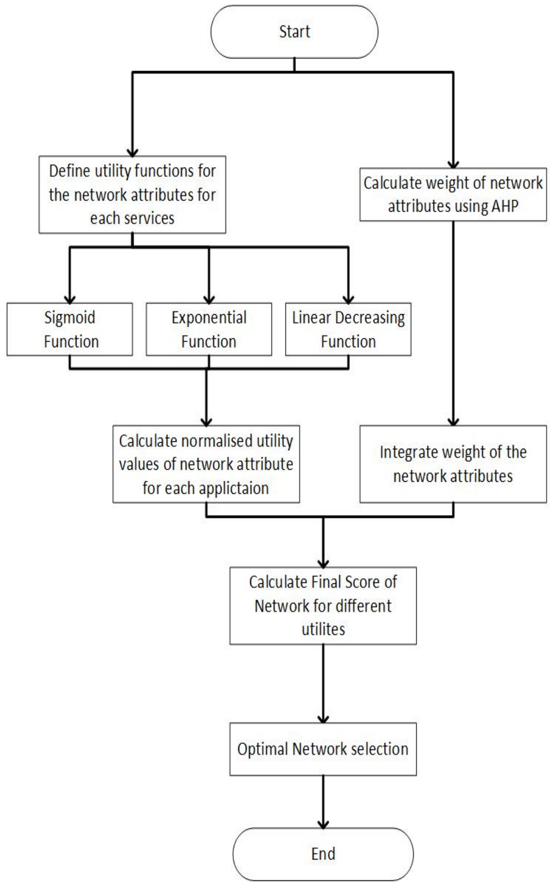

Figure 4.5: Flow Chart of Proposed Network Selection Algorithm

energy efficiency, delivery probability, network bandwidth, and delay can be calculated appropriately.

Utility function Theory-based Network Assessment:

Utility functions measure the amount of satisfaction of each user as per different attributes of each network alternative. Furthermore, not only attributes, the selection of network varies as per the applications/ services selected by users. To evaluate the decision factors of network selection, we design utility functions to map different decision factors to the corresponding utility metrics. Utility functions are defined for different decision criteria of network alternatives and application requirements. We consider user requirements as per their profile, delay-tolerant indicator (DTI), both network properties, and QoS requirements. Generally, there are three types of utility functions used for network selection. 1) Sigmoid function 2) Monotonically increasing function 3) Linearly decreasing function. These functions are further categorized as per beneficial or non-beneficial criteria. The sigmoid utility function is used with a given minimum and maximum requirements. Bandwidth and Energy efficiency is a beneficial criterion and can be represented as a sigmoid function. As per utility theory, all the defined utility functions should be satisfied with twice differentiability, monotonicity, and concavity-convexity [169]. Therefore, we design different utility functions for different objectives. The value of the utility function lies between 0 to 1. For the most satisfied user, it's 1 and for the least satisfies user, it counts as 0.

Utility function for Energy Efficiency(EE)

In this utility function EE, as discussed, is a beneficial criterion, and the energy-efficient utility function will be modeled as a sigmoid curve. The sigmoidal utility function is defined as below:

$$u(e) = \frac{1}{1 + xe^{c(e_{avg} - e)}}; e > 0 \tag{4.2}$$

Where e_{avg} and e represents the average network energy efficiency and network energy-efficiency. x is used as a constant value that is always greater than zero $(x > 0)$. The notation c is used to denote the sensitivity of network attributes affecting energy efficiency. The utility function for energy efficiency is plotted in Fig. 4.6, we can make sure that the utility function is monotonic and concavity convex. The physical meaning of Eq. 4.2 is that a higher network energy efficiency e results in a larger utility function $u(e)$ and a preferable network. This indicates that the well-defined utility function $u(e)$ can successfully be used for optimal network selection.

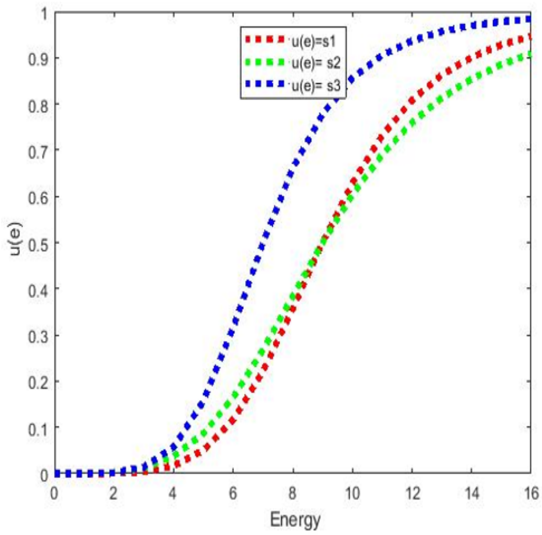

Figure 4.6: The Utility Function for Energy Efficiency

Utility function for Network Bandwidth

Network Bandwidth is an important attribute for network selection. For three of these networks, network bandwidth has a different value. When network bandwidth is lower than required bandwidth as per different service requirements, then it's a compromise in QoS, and there will be a loss of packets. We are using the following utility function to define bandwidth requirements for different applications.

$$u(b) = \begin{cases} 0, & ; b < b_{min} \\ \frac{(\frac{b}{b_{med}})^{x4}}{1+(\frac{b}{b_{med}})^{x4}} & ; b \leq b_{min} \leq b_{med} \\ 1 - \frac{(\frac{b_{max}-b}{b_{max}-b_{med}})^{x4}}{1+(\frac{b_{max}-b}{b_{max}-b_{med}})^{x4}} & ; b_{med} \leq b \leq b_{max} \\ 1 & ; b > b_{max} \end{cases} \tag{4.3}$$

b_{min} and b_{max} defines the minimum and maximum bandwidth of each network. In addition to that, b is the actual bandwidth required by the user as per the services required. Same as an energy utility function. All the utility function fulfills the condition that is twice differentiable, monotonic, and concavity convex and shown in Fig. 4.7.

Hence, larger utility function $u(b)$, and more optimal network selection.

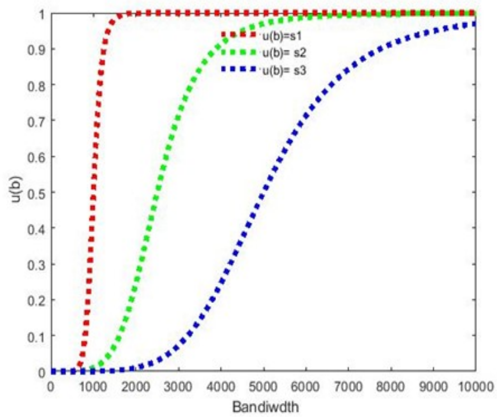

Figure 4.7: The Utility Function for Bandwidth

Utility function for Delay Tolerance

Generally, incremental latency value is acceptable in Delay Tolerant Network (DTN). While designing the utility function for network delay tolerance, it is quite obvious that a larger network delay value will lead to a lower corresponding utility value. The network delay criterion is a decreasing metric. Delay varies in both networks as per the data volume. $u(d)$ is defined as a utility function for the delay as below:

$$u(d) = 1 - u'(d) \tag{4.4}$$

$$u'(d) = \begin{cases} \frac{(\frac{d}{d_{med}})^{x3}}{1+(\frac{d}{d_{med}})^{x3}} & ; d \le d_{min} \le d_{med} \\ 1 - \frac{(\frac{d_{max}-d}{d_{max}-d_{med}})^{x3}}{1+(\frac{d_{max}-d}{d_{max}-d_{med}})^{x3}} & ; d_{med} \le d \le d_{max} \\ 1 & ; d > d_{max} \end{cases} \tag{4.5}$$

Where d_{max} is the maximum delay and x is the sensitivity factor for delay calculation among both networks. The utility function for the delay is also twice differentiable, monotonic, and concavity convex and shown in Fig. 4.8.

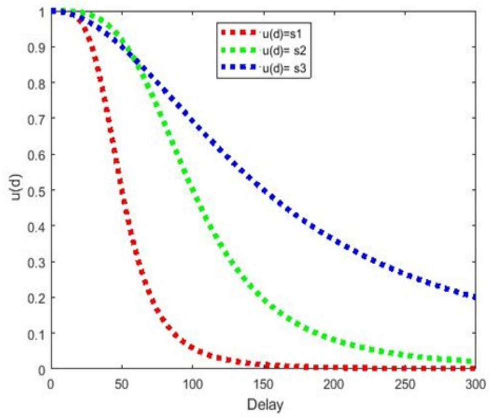

Figure 4.8: The Utility Function for Delay Tolerance

Utility function for Delivery probability

Delivery probability is to be defined as the volume of data to be sent using any of the networks. We define utility function of delivery probability as $u(dp)$, where $dp\epsilon[0,1]$ in case of successful delivery, it is 1 and otherwise for packet loss, it will be considered as 0 or otherwise, it lies in between 0 and 1. dp is the delivery probability obtained and dp_{max} is the maximum delivery probability acceptable to the user.

The physical meaning of Eq. 4.6 is that a higher delivery probability value results in a larger utility function $u(dp)$ and a preferable network, which is shown in Fig. 4.9.

$$u(dp) = \begin{cases} \frac{dp}{dp_{max}} & ; 0 \leq dp \leq dp_{max} \\ 1 & ; dp > dp_{max} \end{cases} \tag{4.6}$$

4.4.3 MADM

This step helps to decide different networks based upon the weights obtained from the decision matrix, alternatives, and different criteria.

Analytical Hierarchical Process (AHP)

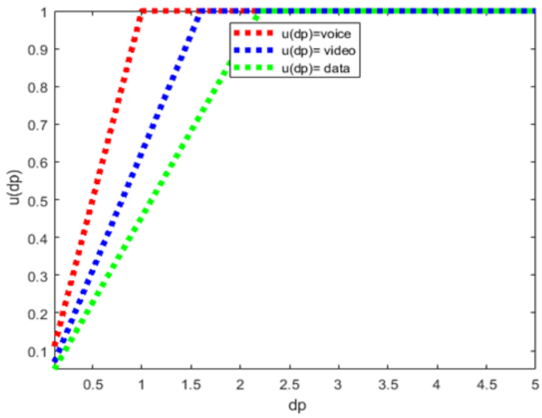

Figure 4.9: The Utility function for Delivery Probability

The analytical Hierarchical process (AHP) method is a multi-criteria decision-making process for network selection. It was being developed at the Wharton School of Business by Thomas Saaty (1980) [170]. In this process, a problem is structured into the form of hierarchy with an objective as a goal to achieve and sub-objectives/criteria are used to decide among different alternatives. AHP works on the function of priority and rank to evaluate subjective weight to achieve the goal. We have used this process to select a best-featured network from the given alternatives for the given service class based on criteria – Energy Consumption, Bandwidth, Delay, and Delivery Probability. We have also used this process for choosing a priority of network types for each data type.

The respective analysis performed, and the code implemented will help our device to choose the best network (for different data types) from the given ones. Our decision problem is also hierarchal and involves interaction and dependence on other elements. Network weighing is an important factor to characterize the network performance and user's preference. We are using the hierarchy analysis method to allocate the appropriate weight to each selection metric.

We categorize further traditional networks into WLAN and UMTS networks for impartial scheming with different attributes as shown in Fig. 4.10 The logical flowchart of the AHP algorithm considers the hierarchical structure with the main goal, multiple criteria, and network alternatives to select. We have defined utility functions for all the attributes for a network assessment. A user's preference will be based on multiple criteria for network selection. We assume that WLAN users have wireless access to their system but with a fixed location or we can say a local network and they use all their devices to avail the services and disseminate data to nearby RSUs for further transmission. However, they have good speed and bandwidth value. On the other hand, UMTS is a mobile cellular device and can roam around with its data plans. But, with limited bandwidth and larger delay as per delivery probability and data network range.

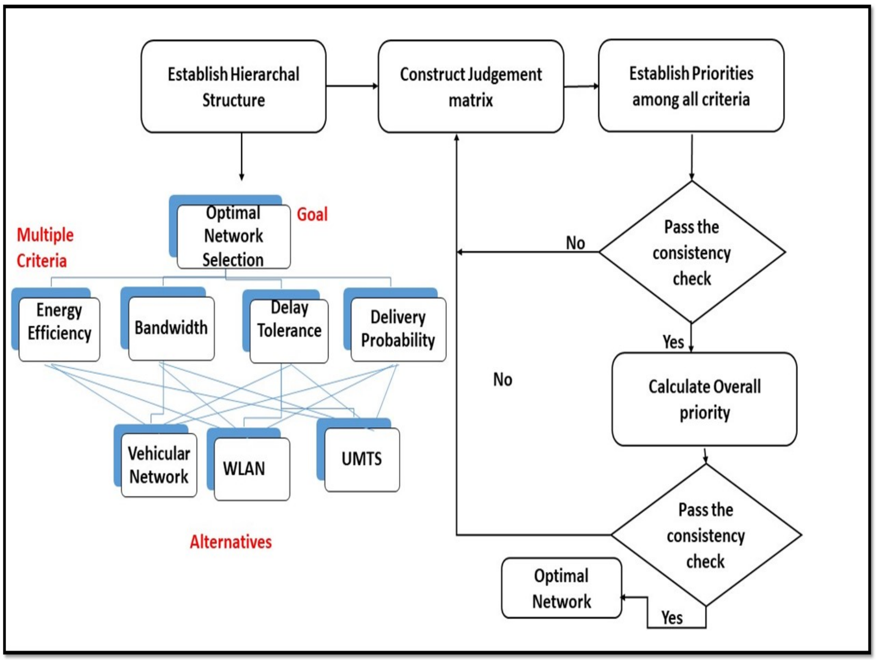

Figure 4.10: AHP for Network Selection

1. Firstly, we subdivide a problem into further subproblems by defining an objective function, criteria, and possible alternatives. Here, the objective is our goal to achieve optimal network selection. The multiple criteria are the factors affecting the preference for selection.

2. Develop the hierarchy model of all objectives along with their elements to obtain

the priorities of criteria through pairwise comparison matrices.

3. Construct a Pair-wise comparison matrix for each criterion of hierarchal structure in such a way that all associated criteria get compared with each other as per the intensity of importance with respect to the scale. We believe that a pairwise comparison between alternatives helps for qualitative judgment. This qualitative pairwise comparison follows the importance scale as shown in table 2.

$$P = \begin{array}{c} \begin{array}{cccccc} C_1 & C_2 & \cdots & C_j & \cdots & C_N \end{array} \\ \begin{pmatrix} 1 & x_{1,2} & \cdots & x_{1,j} & \cdots & x_{1,N} \\ x_{2,1} & 1 & \cdots & x_{2,j} & \cdots & x_{2,N} \\ \vdots & \vdots & 1 & \vdots & \ddots & \vdots \\ x_{i,1} & x_{i,2} & \cdots & 1 & \cdots & x_{i,N} \\ \vdots & \vdots & \ddots & \vdots & 1 & \vdots \\ x_{M,1} & x_{M,2} & \cdots & x_{M,j} & \cdots & 1 \end{pmatrix} \end{array} \begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_i \\ \vdots \\ C_N \end{array} \tag{4.7}$$

Preferences as per importance	**Definition**
1	Equal Importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values

Table 4.2: Criteria importance scale in a pairwise comparison.

4. Normalization of given matrix P, which is now denoted as P_{Norm}

$$P_{Norm} = \begin{array}{c} \begin{array}{cccccc} C_1 & C_2 & \cdots & C_j & \cdots & C_N \end{array} \\ \begin{pmatrix} 1 & z_{1,2} & \cdots & z_{1,j} & \cdots & z_{1,N} \\ z_{2,1} & 1 & \cdots & z_{2,j} & \cdots & z_{2,N} \\ \vdots & \vdots & 1 & \vdots & \ddots & \vdots \\ z_{i,1} & z_{i,2} & \cdots & 1 & \cdots & z_{i,N} \\ \vdots & \vdots & \ddots & \vdots & 1 & \vdots \\ z_{M,1} & z_{M,2} & \cdots & z_{M,j} & \cdots & 1 \end{pmatrix} \end{array} \begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_i \\ \vdots \\ C_N \end{array} \tag{4.8}$$

$$\text{where, } z_{i,j} = \frac{x_{i,j}}{\sum_{i=1}^{N} x_{i,j}} \tag{4.9}$$

5. Contributions of each normalized metric multiplied by the assigned importance weight wj and can be calculated for the ith criteria as below:

$$P_w = \frac{\sum_{i=1}^{N} Z_{i,j}}{N} \text{with} \sum_{i=1}^{N} P_w = 1 \tag{4.10}$$

Such that, P_w is the weight vector.

6. Now, let's calculate the consistency index, where $\lambda_m ax$ is the largest eigenvalue of P_{Norm}, and it is determined from the eigenvalue computation of P_{Norm}.

$$CI = \frac{\lambda_{max} - N}{N - 1} \tag{4.11}$$

7. In the last step, we evaluate the consistency of the comparison, using the Consistency Ratio (CR) defined as:

$$CR = \frac{CI}{RI} \tag{4.12}$$

Where RI is the index used for the number of attributes used in decision making and rank the network based on it. For acceptable $CR < 0.1$, otherwise pairwise comparison is to be done again.

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table 4.3: The Random Index

In such a way, AHP helps for network selection among different networks based upon different attributes. After the selection of the public transport network, the next section will elaborate further about allocating data onto buses as per their stay time at each bus stop.

4.5 Data Allocation Model onto Buses

The objective of our SDCA is to select an optimal network and allocating data over the selected network. As discussed before, we have three networks such as Vehicle, UMTS, and WLAN to offload data as per different criteria. WLAN and UMTS are both traditional ways of disseminating data over the internet and in the case of vehicles/buses, we will have to consider each bus stop as an offloading spot to upload data.

To allocate data onto buses, we need to find the contact duration of buses and throughput at each bus stop. A bus stops for a shorter period at passing stops and for a longer period at parent stops(source/destination). We already used ANN in our previous chapter to predict bus arrival time at each stop, which helped us to know bus early arrival or late arrival. However, bus stay time depends upon many factors such as passenger activity, time of day, route type, and bus floor. Moreover, all bus's real-time information is periodically being sent to the base station so that they can keep track of the vehicles and which ultimately helps to determine the link stability and data offloading at each bus stop. To obtain the maximum efficiency in the offloading process in our proposed work, we consider both types of stops including stopping stops and passing stops. Stopping stops further include all the stops, where buses stop for a longer or shorter duration. Parents stops are the source or destination stops and will stay longer there than other stops under the category of shopping stops. We also assume that bus entering and exit speed will be equal as it slows down while entering at each stop. Additionally, the location of RSU does not affect contact duration as it is placed exactly where the bus stops. Figure 4 9 gives a schematic overview of the operation to offload a large amount of delay-tolerant background data over the road infrastructure between two remote data centers using Bus stops in between.

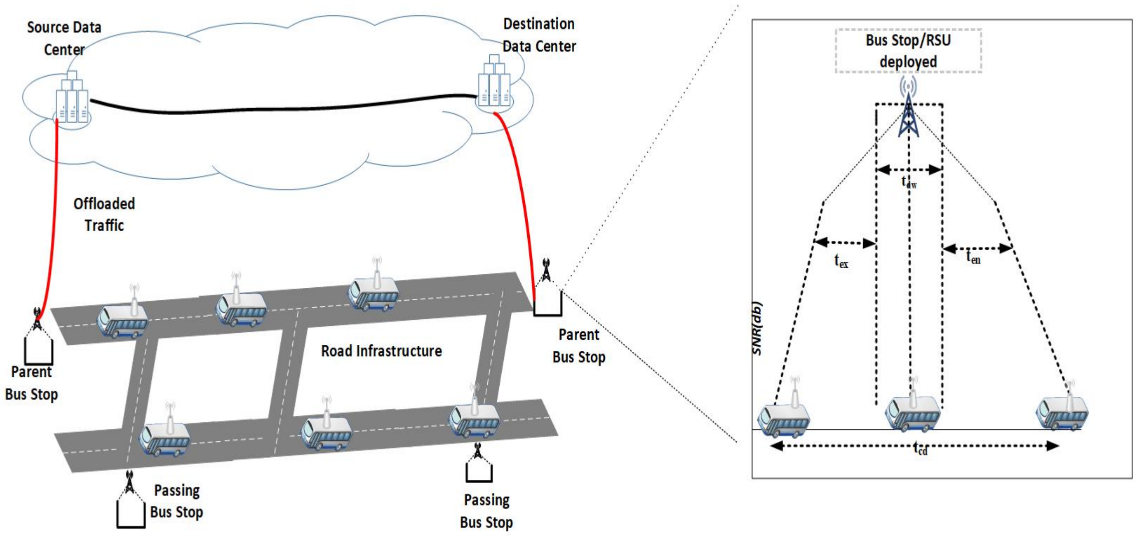

Figure 4.11: Data Allocation Model onto Buses

4.5.1 Data offloading for Stopping Stops

Recall that the objective is to use public transport vehicles to carry large amounts of delay-tolerant data while reducing traffic load from existing infrastructure. All buses pass by bus stops and data can be offloaded as per the stay time, enter time, exit time, and contact duration of the bus into the range of deployed RSU.

$$t_{cd} = t_{en} + t_{dt} + t_{ex} \tag{4.13}$$

where, Where t_{en}, t_{dt}, t_{ex} and t_{cd} are the bus entering time, dwell time, exit time and contact duration at each bus stop, respectively. We assume that bus entering/exit speed is same and gradually decreases/increases with the speed(s) until it further reaches next bus stop. We state the communication range (CR) for each bus while coming in contact with RSU deployed at each bus stop.

$$d_{ex} = \frac{1}{2}st^2 + v_0t + d \tag{4.14}$$

Where d is the distance between RSU deployed and the bus during stay time. d_{ex} is the distance after t seconds of the bus leaving the stop or from the range of deployed RSU. Bus stops at stopping stop, in this case, bus leaves a station from standstill situation and therefore $v_0 = 0$

To calculate data throughput, it is important to know received signal power(rsp), it depends upon the distance from deployed RSU and the bus arrival or stay time. We will be calculating $rsp(d)$ using the distance between RSU and log-normal shadowing path loss model as follows

$$rsp(d) = P_r - 10\phi\log(d_{ex} \,/\, d_{ref}) + \sigma \tag{4.15}$$

Where P_r is the received power from RSU at reference distance d_{ref} , ϕ is the path loss component (PLE), σ is the normally distributed random variable. P_r can be further obtained by following

$$P_r = P_{tr} - 20\log 4 * \pi * d_{ref} \,/\, \lambda \tag{4.16}$$

Where, P_{tr} is the transmitted power and λ is the signal wavelength in meters and can be obtained from $\lambda = c/f$, where c is the speed of light and f is the frequency. d is the distance from the RSU, and the bus and effective distance can be $2d$, the diameter of the radius coverage area of RSU deployed at bus stops. Every bus will be in coverage as it starts entering at bus stops, there data will start offloading at a distance from 0 to

2d meters. Moving further, received signal power rsp also depend upon the time (t), therefore considering $d_{ref} = 1m$, rsp with respect to time is defined.

$$rsp(t) = P_r - 10\phi \log(\frac{1}{2}st^2 + d) + \sigma \tag{4.17}$$

We will be using the IEEE802.11 module as an interface to make a connection between bus and RSU, the maximum throughput is calculated based upon signal to noise ratio $SNR(db)$, which can be calculated as follows:

$$SNR(in\ db) = rsp(t) - n_b \tag{4.18}$$

Where n_b is the background noise, Furthermore, $SNR(db)$ based upon time can be obtained as:

$$SNR(t) = P_r - n_b - 10\phi \log(\frac{1}{2}st^2 + d) + \sigma \tag{4.19}$$

The maximum bit rates λ^{max} rates is attained from MCS mapping tables bandwidth b_w based upon different frequencies(f), number of spatial streams(SS) and duration of the guard interval(GI).

$$\forall snr^i \leq snr(t) < snr^{i+1} \rightarrow \lambda^{max} \tag{4.20}$$

Where, $i = 0, 1, 2......9$ from MCS index to attain maximum bit rate and F is the mapping function. The throughput $\mu_{(en/ex)}$ can be obtained from maximum data rate (λ^{max}) and MAC efficiency (ρ).

$$\mu_{en/ex} = \lambda^{max}\rho \tag{4.21}$$

Hence, offloading capacity (O_c) is the sum of the capacity for stopping bus stop or non-stopping bus stops as defined above as two different cases.

$$O_{stopping} = \sum_{i=1}^{N_{stp}} (\mu_{st}^{i} * t_{st}^{i} + 2 \sum_{t=0}^{t_i^{max}} \mu_{(en/ex)}^{i} * \Delta t^{i}) \tag{4.22}$$

Where μ_{dt}^{i} is the maximum throughput at dwell time t_{st}^{i} for all the stopping bus stops. Parent bus stops will also be considered under stopping bus stops. i is the range from 1 up to N number of stops $(1 \leq i \leq N_{stp})$ referring to all stops including parent stops.

4.5.2 Data offloading for Passing Stops

The bus just passes through a passing stop with a constant speed (i.e.$s = 0$) and there are no passengers to board on the bus stop, in this case, bus comes in contact of any bus stop for a very short duration. Where time(t) is defined.

$$t = 2t_{ps} \tag{4.23}$$

Where $t_p s = d_{ex}/v_{ps}, v_{ps}$ is the velocity at the time of passing stops. Substituting values in (3.11) is

$$d_{ex} = v_{ps} * t + d \tag{4.24}$$

Furthermore, to obtain received signal power again for passing stops is defined as

$$rsp(t) = P_r - 10\phi \log(v_{ps} * t + d) + \sigma \tag{4.25}$$

The offloading efficiency of passing stop is

$$O_{passing} = 2 \sum_{j=1}^{N_{ps}} \sum_{t=0}^{t_j^{max}} \mu_{ps}^{j} * \Delta t^{j}) \tag{4.26}$$

Where, j is the list of stops, where bus passes by $(1 \leq j \leq N_{ps})$

4.5.3 Total Offloading Efficiency of the Public Transport Network

We have analysed offloading efficiency for two different types of bus stops. If the bus stops for some time at any stopping bus stop, then we obtain offloading efficiency of stopping bus stop $O_{stopping}$ from equation 4.22. On the other hand, if the bus just passes through any passing stops, then offloading efficiency $O_{passing}$ will be calculated from equation 4.26. The total offloading efficiency $O(Total)$ of public transport network can be acquired from the equation

$$O_{PT} = O_{stopping} + O_{passing} \tag{4.27}$$

By substituting (4.22) and (4.26) into (4.27), we have

$$O_{PT}(Total) = \sum_{i=1}^{N_{stp}} (\mu_{st}^{i} * t_{st}^{i} + 2 \sum_{t=0}^{t_i^{max}} \mu_{(en/ex)}^{i} * \Delta t^{i}) + 2 \sum_{j=1}^{N_{ps}} \sum_{t=0}^{t_j^{max}} \mu_{ps}^{j} * \Delta t^{j}) \tag{4.28}$$

4.6 Performance Study

To evaluate the performance of our network selection procedure, we will consider again the Auckland public transport network as a public vehicle to choose among three network alternatives. Normally, the urban area is covered by heterogeneous wireless networks including WLAN, UMTS, and public vehicles/buses. All these networks bear different characteristics as described above. For vehicular network selection, the vehicle must be into the range of the network to consider as a selection option based upon the user's preference. For simplification, we make the following assumptions:

Assumption 1 We are considering three types of networks: WLAN, UMTS, and vehicular network. For further information related to the vehicular network, only scheduled public transport vehicles are involved. WLAN and UMTS network cover the whole region, while VANET covers partially, only within a specified range of bus-stop. Additionally, vehicle-to-vehicle communication is not considered.

Assumption 2 For any of the network selection, there is a predefined bandwidth and range defined, if it is available then only network selection is possible. Additionally, the characteristics of networks, bandwidth, delay tolerance, energy efficiency, and delivery probability are defined as influencing factors. As defined SDCA model, the controller looks for user's profile, flow table and take network selection decision accordingly. Every user has different preferences based on their requirements. We will be using the AHP method to assess each user's requirements and preferences.

4.6.1 Auckland Central: Case Study

We will be considering Auckland Central as an area for data analytics and the locations to show the vehicle's distribution among different bus-stops. We have considered four different locations: City Center, Britomart, Wellesley Street, and Auckland Hospital. All these bus stops are equipped with local storage for data storage to upload or download onto buses coming onto that route. Furthermore, all user's profile gets checked as per source and destination location of data transmission and buses get selected based upon that.

We will evaluate the performance of the AHP method using simulations over MATLAB based upon different utility values for all attributes. We simulate for our goal to have optimal network selection based upon different criteria and alternatives. User

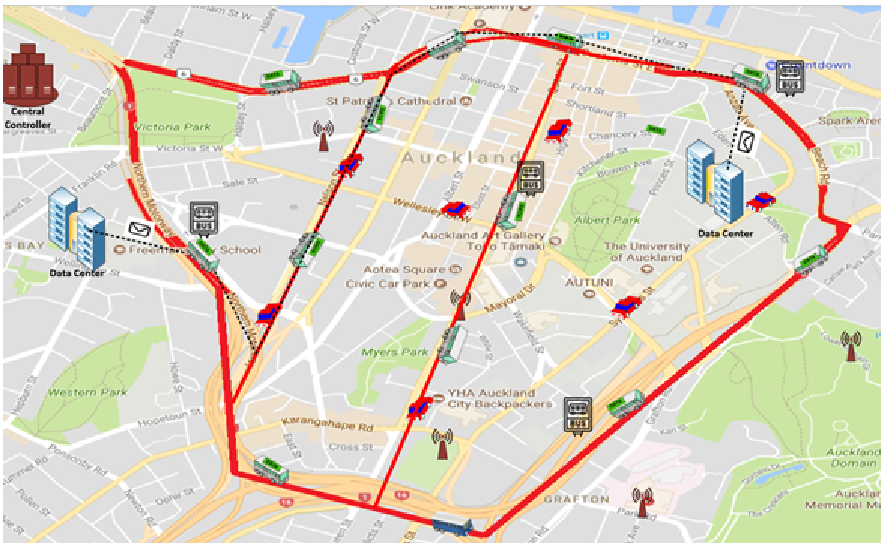

Figure 4.12: Auckland Central map with locations

preferences play an important role in the selection of the best available network in a heterogeneous environment. The proposed method for determining the user's preference is based upon the basic idea of AHP.

Service 1

We have categorized our services with all the different criteria as defined below. The first service is to be initialized from the data center (DC1) to the data center (DC2). The controller helps to select optimal network as per their preferences being decided for different criteria defined above such as Energy Efficiency (EE), Bandwidth (B), Delivery probability (DP), and Delay Tolerance (DT) important attributes. The utility values have been defined for all attributes above in Section 4.4.2.

$$S_1 =< EE, BDV, DT >$$

In this Service $1(S_1)$, we assume that this service is for non-real-time applications

Attributes	Energy Efficiency	Bandwidth	Delay Tolerance	Delivery probability
Energy Efficiency	1	7	9	3
Bandwidth	1/3	1	7	2
Delay Tolerance	1/9	1/7	1	1/5
Delivery probability	1/3	1/2	5	1

Table 4.4: Pairwise Comparison Utility matrix as per importance scale

Attributes	Energy Efficiency	Bandwidth	Delay Tolerance	Delivery probability	Critera Weight
Energy Efficiency	1	7	9	3	0.530345069
Bandwidth	1/3	1	7	2	0.164911216
Delay Tolerance	1/9	1/7	1	1/5	0.041457905
Delivery probability	1/7	1/2	5	1	0.280751063

Table 4.5: Normalised score table for all the attributes with the weight factor

Attributes	Energy Efficiency	Bandwidth	Delay Tolerance	Delivery probability	Critera Weight	Priority Vector (P_w)
Energy Efficiency	1	3	9	7	0.530345069	0.5289
Bandwidth	1/3	1	7	2	0.164911216	0.1582
Delay Tolerance	1/9	1/7	1	1/5	0.041457905	0.0366
Delivery probability	1/7	1/2	5	1	0.280751063	0.2763

Table 4.6: Normalised score table with priority vector

such as video surveillance data to be accumulated at the data center and can be delayed for up to 13 hours. There are three possible networks to choose from UMTS, WLAN, and public transport. When the end-user sends and receives big data-files such as backup storage or huge data in TB or PB, this scheme applies. This is one of the classical data communication schemes that on an overall level is characterized by that the destination is not expecting the data within a certain time. The scheme is thus more or less delay tolerant. Eg: background downloading of mails, sending of data with google drive, data backup. In this case, we are giving more importance to the energy efficiency factor than other attributes as we can bear delay for this application or services. Now, the same procedure will be followed for all the attributes as per services as defined in all tables 4.4, 4.5 and 4.6.

λ_{max} = 4.178069312 ; CI = 0.059356437 ; CR = 0.065951597 < 0.1

This pair-wise matrix also passes a consistency check, which means that priority is selected correctly.

Service 2

The next service is more for the urgent delivery of data. In this case, the delay-tolerant indicator is about 3 hours and the data volume is 64TB. Same as before, Service 2 (S_2), will be having similar attributes but different tendencies. This service is real-time applications such as Video-on-Demand. These services are delay-sensitive and therefore can't be delayed for more than 3 hours. However, due to large volume of data, still giving more importance to energy efficiency and delay attribute than other attributes. It is the service class with the highest QoS requirements and switches from one network to another quickly as per user's profiles such as telephony speech, VoIP, video conferencing, and other real-time activities. If a user is connected to WLAN and loses connection, then they can switch to UMTS for QoS. The same procedure will be followed for all attributes for Service 2:

Attributes	**Energy Efficiency**	**Bandwidth**	**Delay Tolerance**	**Delivery probability**
Energy Efficiency	1	7	1	5
Bandwidth	1/7	1	1/7	2
Delay Tolerance	1	7	1	7
Delivery probability	1/5	1/2	1/7	1

Table 4.7: Pairwise Comparison Utility matrix as per importance scale

Attributes	Energy Efficiency	Bandwidth	Delay Tolerance	Delivery probability	Critera Weight
Energy Efficiency	1	7	1	5	0.42274576
Bandwidth	1/7	1	1/7	2	0.08567345
Delay Tolerance	1	7	1	7	0.45678945
Delivery probability	1/5	1/2	1/7	1	0.06435676

Table 4.8: Normalised score table for all the attributes with the weight factor

Attributes	Energy Efficiency	Bandwidth	Delay Tolerance	Delivery probability	Critera Weight	Priority Vector (P_w)
Energy Efficiency	1	7	1	5	0.42274576	0.4163
Bandwidth	1/7	1	1/7	2	0.08567345	0.0782
Delay Tolerance	1	7	1	7	0.45678945	0.4455
Delivery probability	1/5	1/2	1/7	1	0.06435676	0.0599

Table 4.9: Normalised score table with priority vector

λ_{max} = 4.156390957 ; CI = 0.052130319 ; CR = $0.057922576 < 0.1$

This pair-wise matrix also passes a consistency check, which means that priority is selected correctly. We have calculated weight for all three types of services by user's preferences for different attributes.

Service 3

The next service is different from the previous two. In this case, delay tolerance is 6 hours and data volume is 32TB. Service $3(S_3)$, will be having consistent attributes but different inclinations. This service is not that low in data volume in comparison with others. These services are delay-sensitive and therefore can't be delayed for more than 6 hours. In this case, again, the user has all three options to disseminate data. The controller will first look for all the network options including WLAN, UMTS, and if there are buses available to carry data within the given timeframe. The same procedure will be followed for all attributes:

Attributes	Energy Efficiency	Bandwidth	Delay Tolerance	Delivery probability
Energy Efficiency	1	1/6	1/6	1/7
Bandwidth	6	1	3	1
Delay Tolerance	6	1/3	1	1/5
Delivery probability	7	1	5	1

Table 4.10: Pairwise Comparison Utility matrix as per importance scale

Attributes	Energy Efficiency	Bandwidth	Delay Tolerance	Delivery probability	Critera Weight
Energy Efficiency	1	1/6	1/6	1/7	0.05355183
Bandwidth	6	1	3	1	0.36439882
Delay Tolerance	6	1/3	1	1/5	0.15369319
Delivery probability	7	1	5	1	0.4540202

Table 4.11: Normalised score table for all the attributes with the weight factor

Attributes	Energy Efficiency	Bandwidth	Delay Tolerance	Delivery probability	Critera Weight	Priority Vector (P_w)
Energy Efficiency	1	1/6	1/6	1/7	0.05355183	0.0459
Bandwidth	6	1	3	1	0.36439882	0.3613
Delay Tolerance	6	1/3	1	1/5	0.15369319	0.1499
Delivery probability	7	1	5	1	0.45402002	0.4429

Table 4.12: Normalised score table with priority vector

λ_{max} = 4.234869383 ; CI = 0.078289794 ; CR = 0.08698866 < 0.1

This pair-wise matrix also passes a consistency check, which means that priority is selected correctly. We have given importance to different attributes as per different services. Next, we claculated criteria weight for all the attributes and then, added priority vector to all of the attributes as per differet services. Based upon these calcualtions,next, we will rank our network for different services.

4.6.2 Network Selection for Different Services

Today's multi-user multi-technology multi-application multi-provider environment requires the development of new technologies and standards that seek to provide dynamic automatic network selection decisions through seamless global roaming within this heterogeneous wireless environment. In the context of future wireless networks, to achieve an optimal network selection as per different services and their preferences. We have discussed the AHP procedure and utility theory for all the attributes weighing and preferences. Now, the AHP procedure will help us to weigh different attributes for all our services. In our work, we are defining the traditional network and vehicular network as an alternative to choose from and the available list is $I_{an} = (W, U, V)$. Algorithm 2 illustrates the whole process for optimal network selection based upon different services.

Algorithm 2: Optimal Network Selection

Input : Different services as per user's profile: energy efficient e_u, delivery probability dp_u, delay demand d_u, available bandwidth b_i of both networks, Available network list I_{an}

Output : Decision factor weight and rank of selected newtork, energy efficient weight w^e, bandwidth weight w^b , delivery probability weight w^{dp}, Delay weight w^d

According different services of users, build decide hierarchy structure $P = x_{(1,j)}, x_{(2,j)}, ..., x_{(M,j)}$;
Loop 1: Construct decision Matrix P;
Loop 2: Calculate the weight of heirarichy $x_{(M,j)}$; including energy efficient weight w^e, bandwidth weight w^b, data volume weight w^dv, delay weight w^d of heirarichy;
decide whether hierarchy $z_{(i,j)}$ is consistent;
If not, go back to **Loop1**;
if $z_{(i,j)} < N$, go back to **Loop2**;
calculate the total weights; then attain energy efficient weight w^e, bandwidth weight w^b, delivery probability weight w^{dp}, delay weight w^d;
decide whether the whole hierarchy is consistent; if not, go back to **Loop1**;
Get the final Priority vector for all attributes
Rank the network selection score
Exit the procedure;

There is a list of available networks I_{an} = (W, U, V) to choose from. We will collect all the network attribute list I_{an} = $a_1, a_2 \ldots . a_n$ named as energy-efficient e_u, delivery probability dp_u, delay demand d_u, available bandwidth b_i of both networks, Then will follow all the steps to rank the network among all the networks as per different services. We are using this network selection technique only to give the best option as per their requirements to maintain QoS. It is mandatory to pass the consistency check in AHP for an accurate judgment matrix. If any of the matrices don't pass this check, the user will have to give preferences again to the design matrix based upon Table 4.2. We will first analyze public vehicle distribution near bus stops to know the availability of the network to choose from and then further evaluate the performance of all networks for different services. Fig. 4.13 illustrates the criteria weight given to all the attributes as per different services. For example, as discussed before service 1 is having delay-tolerant features and will be considering an energy-efficient data dissemination network. Therefore, the criteria weight will be allocated more on the EE attribute. In such a way, all the weights are distributed as per the service profile. The priority vector is calculated for all the services as per different attributes as shown in Fig. 4.14. The final score is being calculated as discussed in Fig. 4.5. Utility functions are defined already for all the attributes. For all of these services, we will have different utility values. We will score our network-based upon maximum utility value for all the services.

AHP score is the final ranking of all the services as per the preferences given for all the attributes. For service 1, the ranking order is $Vehicle > WLAN > UTMS$ as data is delay-tolerant and can be carried by vehicles for energy-efficient data dissemination as shown in Fig. 4.15. However, for service 2, which is delay-sensitive but for large volume than service 1, also give preference to vehicular network for data delivery in comparison with WLAN and UMTS with a ranking order $Vehicle > WLAN > UTMS$. For service 3, network ranking preference is in the order of $WLAN > UMTS > Vehicle$ for urgent delivery of data to sustain QoS. In-network dynamics, the most important factor is

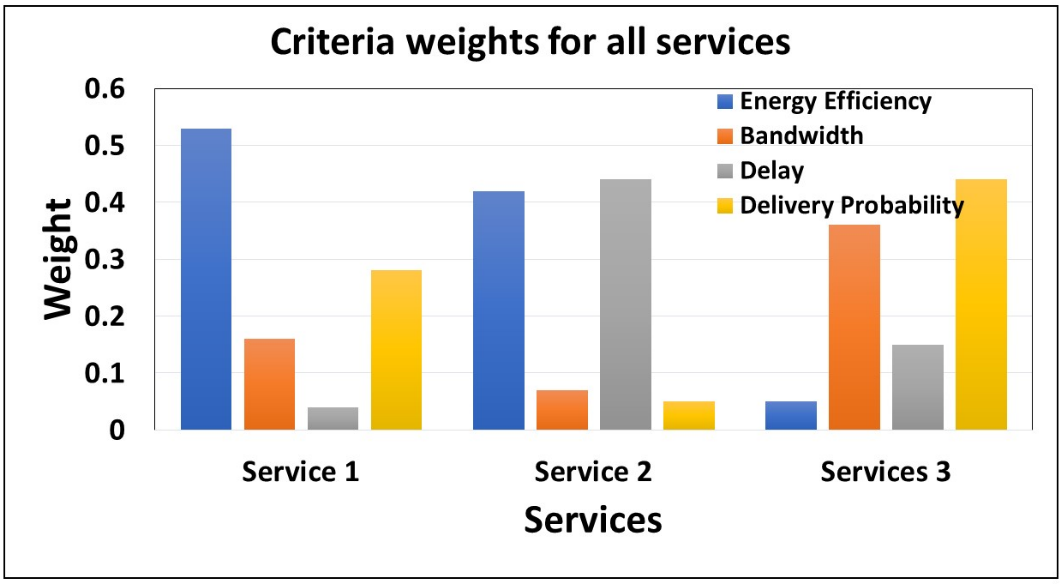

Figure 4.13: Weight Distributed to All Attributes as Per Different Services

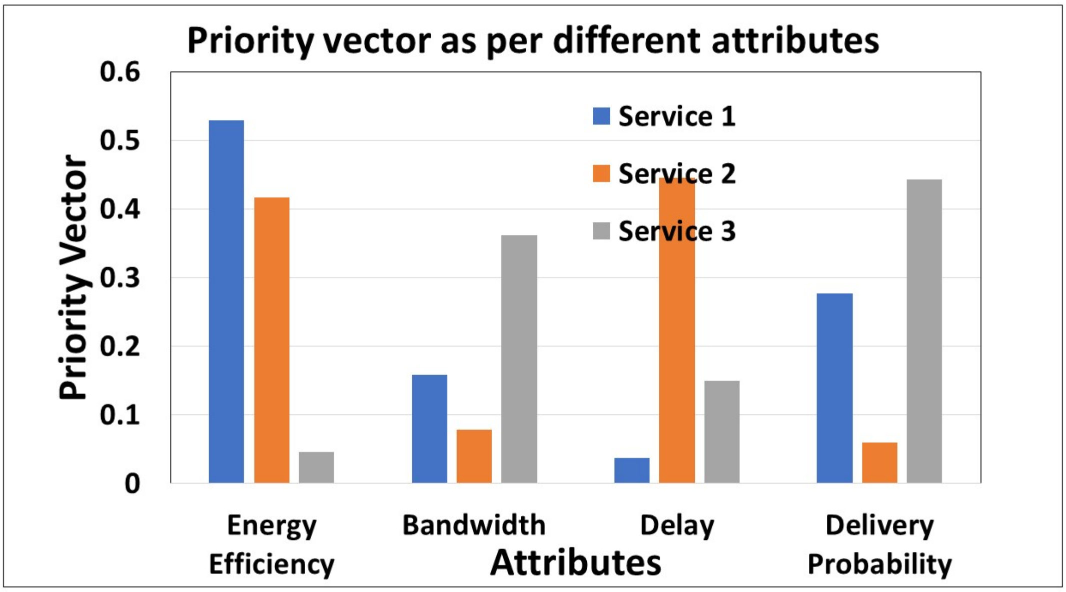

Figure 4.14: Priority Vector for all Services

packet delivery without loss. Our heterogeneous network architecture guarantees the delivery of data by using any of the available networks considering different attributes.

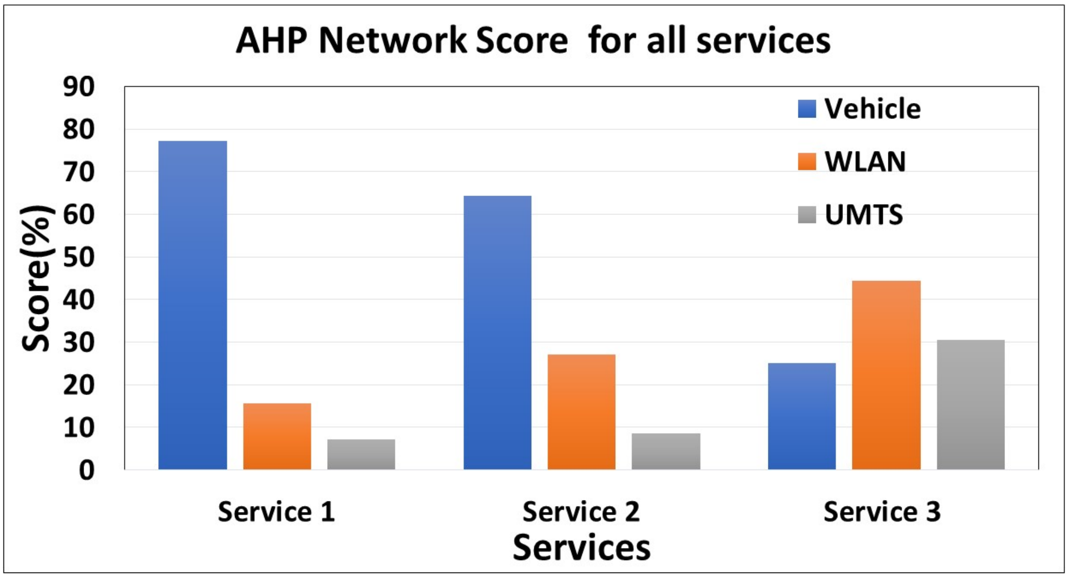

Figure 4.15: Network Ranking for all Services

4.6.3 Data Allocation on AT buses

To evaluate our proposed model of data allocation, we already used AT data set. We assume that an IEEE802.11ac-based WLAN is dedicated to data allocation at each bus stop with different bandwidth such as 20MHz, 40MHz, 80MHz, and 160MHz as per Algorithm 11. This represents the data allocation from the source until the destination for a broadcast job. The data gets allocated onto an available bus near the source location and download at the near destination location. Finally, a data integrity check is done after merging data at the destination stop. We used different parameters to calculate offloading efficiency for stopping stops and passing stops. We will be considering 20 MHZ as the worst-case scenario to evaluate path loss concerning distance and normal distribution for buses when they start approaching bus stops and leave bus stops.

Assuming the stay time of the bus between 20 seconds as the minimum guaranteed value and can increase up to 120 seconds. The velocity of buses at the entering or leaving time will be considered as 20m/s2. To evaluate the performance, we will consider different values of PLE to evaluate the performance for different environmental

Algorithm 3: Data Allocation onto Buses

Input : s: Source location, d: Destination location, t: Stay Time, b: Available bus

Output : Status Message.

while *true* **do**
- $m \leftarrow wait(s)$; `// wait for message from nodes`
- move($\phi_s, \lambda s$) ; `// Reach near source location or bus-stop`
- Available(b,t) ; `// Check for available bus and stay time`
- Upload(s,b) ; `// Uplaod data onto bus`
- move($\phi_d, \lambda d$) ; `// Reach near destination location or bus-stop`
- download(b,d) ; `// Download data from bus`
- **if** $!valid()$ **then**
  - Notify(d)
- **end if**

end while

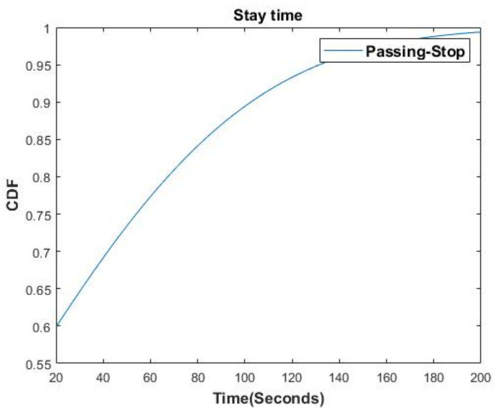

Figure 4.16: Stay Time(S)

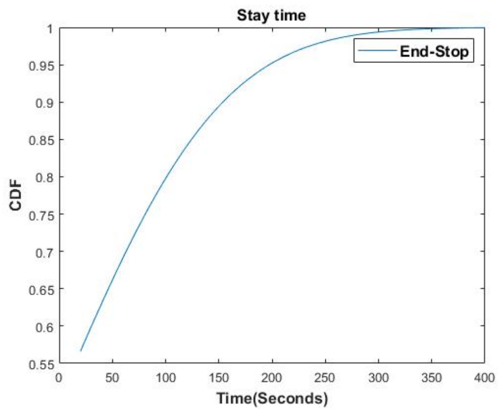

Figure 4.17: Stay Time(S)

conditions at each bus stop with the noise level value to be -90db. Fig. 4.18 shows the path loss and distribution of vehicles obtained from Eq. 4.17. Path loss increases with the distance and reaches up to 80 db. The probability of offloaded data as per the different speeds of the bus is shown in Fig. 4.19.

Fig 4.20 shows the SNR versus time for different PLE values and changes as per timings. We applied the Receiver Based Auto Rate (RBAR) method to theoretically

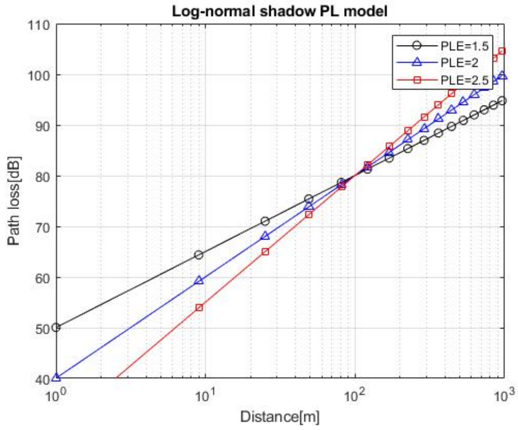

Figure 4.18: RSU distance and Path Loss

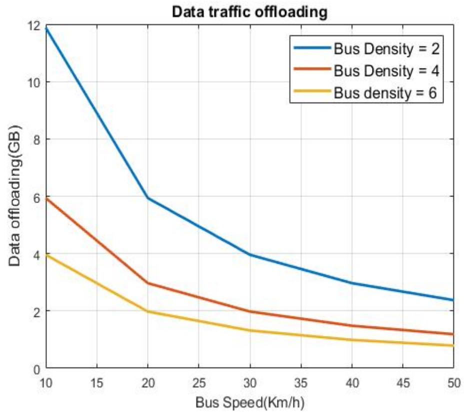

Figure 4.19: Data Offloading Probability

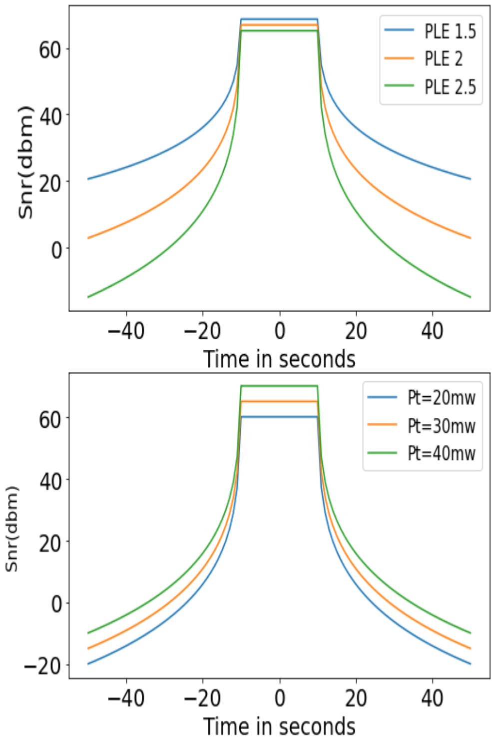

Figure 4.20: SNR Vs Time(s) For different values of a) PLE b)Transmitter Power

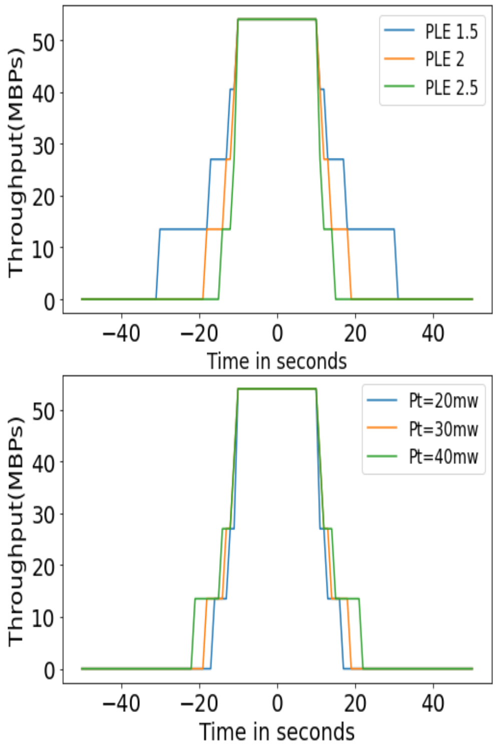

Figure 4.21: Throughput Vs Time(s) For Different Values of a) PLE b)Transmitter Power

estimate the maximum data throughput plotted in Fig. 4.21 for the time to be in coverage of RSU as defined in Eq. 4.18. To illustrate the offloading capacity of upper bound and lower bound for different environments for different values for the transmitter is shown in Fig 4.22. For upper bound, we assumed, GI=400ns, 3 spatial streams and $160MHz$ channel and for lower band, 1 spatial stream, GI=800ns, and $20MHz$ bandwidth. For example, with PLE = 2.5, we can achieve up to $60GB$ offloading capacity for passing stop and $160GB$ for stopping stop from the calculation of Eq. 4.28. By employing new standards, we can achieve more capacity as per each stopping station with maximum data rates.

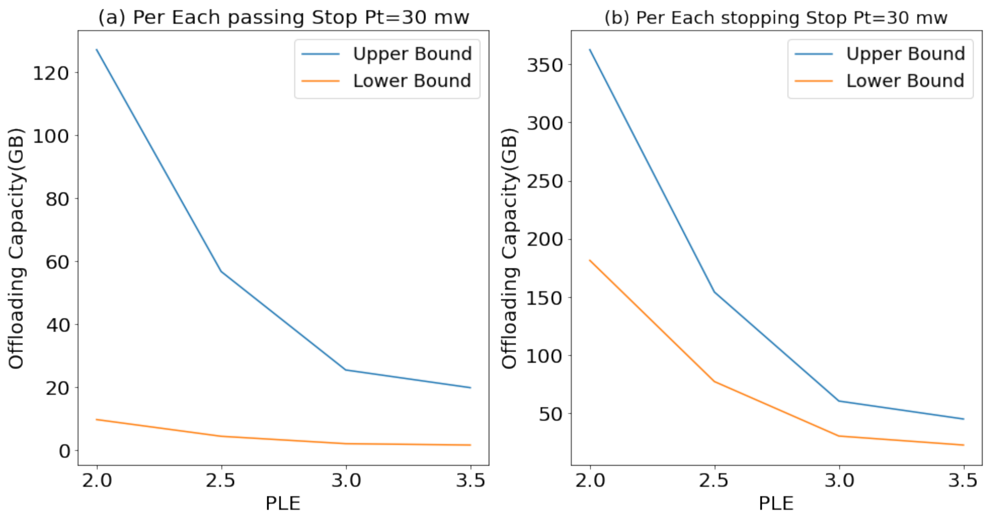

Figure 4.22: Offloading Capacity a)Passing Stops b) Stopping Stop

4.7 Summary

In this chapter, we proposed the concept of SDCA for network selection and data allocation onto buses. The SDC controller makes forwarding decisions and gives connectivity options as per the profiles of users. Our scheme utilizes vehicles' patterned movement and it matches the profile of users from a flow table to make network selection decisions for message forwarding. The controller used MADM method to make an optimal network selection decision among different networks based upon different services. The main implication is that the utility values are defined for all the attributes for the user's satisfaction along with the AHP method for network ranking. The results presented show the network ranking trend among all networks for different kinds of services. Next, we allocated data onto buses as per their stay time, leaving time, and entering time onto the bus stop. The throughput and offloading capacity are analyzed for each stop and terminal and prove that the public transport network can be utilized efficiently for data dissemination in the heterogeneous network.

Chapter 5

Energy Efficient Data Dissemination using PTDD

5.1 Introduction

We introduced the concept of the PTDD as an alternative communication channel to leverage the bandwidth of the traditional network in Section 3.3. We already discussed that PTDD has great potential and can be used for data dissemination with existing infrastructure. Then, we introduced the concept of Software-defined Connectivity architecture for optimal network selection based upon different requirements among different networks and allocated data onto buses after network selection. The objective of this chapter is to validate that PTDD provides the same performance as a traditional network but in an energy-efficient manner.

We are going to propose a novel model of data transmission in heterogeneous networks, where data will be offloaded from the wired network and wireless network towards the scheduled public transport networks such as public buses by using delay-tolerant network techniques. While divesting data from the sources to destinations, there are two data dissemination options: a) through the wired network: which forwards the message through the wired network and gives guaranteed delivery of data, but with the consumption of more energy [171] b) mobile/wireless network: here, users use their mobile devices and forwards messages using their devices which also consume energy. We are going to discover an alternative option to utilize the existing public transport and road infrastructure for sustainable data dissemination. The main contribution of this chapter is as follows:

- We develop an energy consumption model and delay model for heterogeneous networks. These models are being validated using Auckland transport buses. Our proposed outperforms in terms of energy and delay in comparison with the traditional network for delay-tolerant data dissemination and achieve optimal throughput as per bus stay time at the bus stop.

- We present a multi-commodity min-consumption flow problem to optimise energy consumption and carbon emission by using buses. This model aims at minimising energy consumption by either selecting public transport network or a conventional network.

- We formulate capacitated vehicle routing problem to minimise energy consumption to offload the entire set of demands of each bus stop. Our model constraints the objective by the maximum capacity of the bus.

The structure of the chapter is as follows. Section 5.2 illustrates the existing work done in the area of energy-efficient data dissemination. In Section 5.3, we introduce the energy consumption model and delay model in the case of traditional network and public transport network. Sections 5.4, 5.5, 5.6 demonstrated the case study for energy-efficient data dissemination. Finally, Section 5.7 draws the summary of this chapter.

5.2 Background

The public transport market has seen tremendous development in recent decades. Smart cities will improve the quality of life of their citizens with the help of information and communication technologies. To provide energy-efficient data dissemination, several models [56] have been introduced such as implementing visualization, server consolidation, and upgrading older products to new energy-efficient products. These techniques illustrate that base stations and mobile terminals contribute most of the energy consumption. The power-efficient base stations have been designed but they are still struggling with the energy consumption issue since the data volume keeps increasing. Similarly, various technologies are being introduced to truncate energy consumption in wireless networks [172]; however, no clear solution has been provided to overcome this problem.

With the constantly increasing energy consumption in the transmission of a growing amount of data, more energy-efficient and sustainable solutions are necessary to be incorporated into future network architectures. It has been estimated that percentages share of communication technology in global electricity consumption has raised from 8% to 14% in 2010, while in 2020, it will raise from 6% to 21% and 8% to 51% in 2030, respectively. It can be seen that the significant growth of energy consumption is a critical and urgent issue to be addressed. Moving further to offload data for energy efficiency, the delay tolerant data offloading from 3G networks is introduced with a significant impact on the user battery lifetime. Authors in [173] deploy two algorithms for DTN offloading: MiXZones and HotZones. MixZones uses opportunistic, ad hoc transfers between users and network operator's assistance in predicting usage. HotZones exploits the downloading content in the range of Wi-Fi access points in the prediction-based assistance by the operator. This work calculates the amount of offloaded data, delay, and energy efficiency. The study performed in [174] offloads data particularly to public transport vehicles to reduce network congestion due to the high volume of data. The researchers have presented vehicular offloading where delivery relies on upon via the Internet provided by the roadside access points (APs). This offloading scheme helps to sustain a connection for a long time even for non-vehicle users. Many hybrid techniques [93] use the concept of DTN to achieve a reasonable quality of services (QoS) to efficiently deliver the data. Energy consumption depends upon many factors such as distance, interference, signal strength, device model, etc. The hybrid social-based routing technique establishes the delivery of the message when standard MANET routing does not work properly or in the case of a disaster situation. A heterogeneous network (i.e., fixed and mobile infrastructures, mobile nodes) focuses on the use of opportunistic routing to provide various services like control in traffic, security, and environmental issues and making enterprise processes more efficient. The research work in [116] enhanced the previous work with urban transport having prior knowledge of contacts between gateways and ferries to compute routes.

Marincic and Foster [175] developed energy calculation models to transfer data by internet and transport and analyzed that transferring data as atoms is much more energy-efficient than transferring data as bits. They estimated that in some cases, network transfer consumes up to 57% more energy than shipping through transport. They transferred data into the form of atoms by loading it on some portable external hard drive using writing and reading to and from the disk. Cho and Gupta [176] also introduced the concept of transferring data through both internet and disk shipments, they explored the optimal shipment transfer plan considering internet bandwidth traces and shipment cost from FedEx Services. Intending to transfer bulk data such as high-definition multimedia content delivery, Voice calls, or Video Streaming consumes a significant part of the Internet Infrastructure. But now, most of the current cloud storage providers encourage their customers to use hard drives to send or store data. e.g, Amazon Snowball is available for rent which can transport up to 50 terabytes of data.

These kinds of content transfers consume a huge bandwidth and motivate to explore alternative solution via the existing transport network.

5.3 Energy Consumption and Delay Model

A detailed overview of our proposed model PTDD has been discussed in Section 3.3. In the next chapter, we discussed Software-defined connectivity architecture, where SDC Controller dictates the overall network behavior and forwarding strategy as per the demands and selects an optimal network. Now, we will be focusing on the energy consumption model for the traditional core network and public transport network. We are utilizing all the available network to disseminate data from the source until the destination. Our research model has the following principles:

Principle: Before embarking on any architectural design, it is useful to identify the principles embodied in the architecture. These principles allow us to intelligently navigate the infinite space of possible designs. We believe these principles apply to any realistic architecture that uses mechanical backhaul and has goals substantially similar to ours. Our contribution is to take the parameter index as useful parameters to consider and take optimal data dissemination decisions among these three options according to performance metrics.

1. **Lower energy consumption among three layers:** Low energy consumption is possible if we utilize all resources efficiently and reduce CO_2 emission. The traditional network is wired/wireless and communicates effectively. The third option is using a scheduled vehicle to carry data from one location to another. Vehicles are not emitting any extra energy if being used as a data carrier and can be utilized efficiently to save energy consumption.

2. **Utilizing existing public transport:** We are utilizing existing public transport

to make communication more energy-efficient and effective. There is neither any extra cost for arranging new vehicles nor any extra carbon emission to carry data. The vehicle may have some storage room to store data and it may involve one-time investment in the beginning and will compensate many next years.

3. **Acceptable delay:** DTN topology can be used in the case of rural areas and when the traditional core network is not available due to a disaster situation. Moreover, if we have the loose time of requirements and acceptable delay, the third layer can be fully utilized to make network communication more energy efficient. In some cases, this option could bear less delay than the core network.

5.3.1 Energy Consumption Model

We firstly represent the simple and generalized way of energy consumption can be represented in the form of a graph *G(N, L)*, where *N* can be defined as the number of nodes and *L* are directed links *(i,j)* or edges between graph nodes. In the case of a wired and wireless network, energy dissipation occurs where a transmitter transmits power while regenerating radio waves. In such a way, the power amplifier is a big source of energy consumption in transmitting the data. Similarly, the receiver receives these radio waves and consumes energy. To save energy consumption in this process, the only way out is to remedy the signal propagation loss by appropriately setting the power amplifier. The complete procedure employed by sender and receiver can be described as follows:

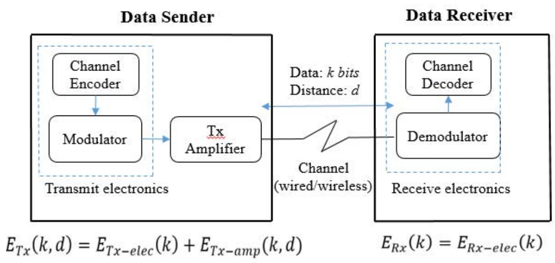

Figure 5.1: A General Energy Consumption Model

Let us consider transmission distance less than threshold value d_0. The free space propagation model with the attenuation parameter of ε_{fx} is used, otherwise, the multipath (mp) propagation model with the attenuation parameter of ε_{mp} is used. For the sender to transmit a volume of k-bits data to the receiver where is *d* away, the energy consumption model can be calculated as below:

$$E_{Tx}(k,d) = E_{Tx-elec}(k) + E_{Tx-amp}(k,d) \tag{5.1}$$

In case of radio transmission,

$$\begin{aligned} E_{Tx}(k,d) &= k \cdot E_{elec} + k \cdot \varepsilon_{fx} \cdot d^2, d < d_0 \\ &= k \cdot E_{elec} + k \cdot \varepsilon_{mp} \cdot d^2, d > d_0 \end{aligned} \tag{5.2}$$

Here, E_{elec} is the energy consumed by the transmitter and it depends on many factors such as digital coding, modulation and filtering signal processing procedures and varies according to that energy consumed by the amplifier depends on the distance to the receiver and the acceptable bit-error rate. Same as for the data receives, the energy consumption can be calculated by:

$$E_{Rx}(k) = E_{(Rx-elec)}(k) = k \cdot E_{elec} \tag{5.3}$$

This general energy consumption model shows that the volume of data *k* and the transmission distance *d* are two critical and variable factors to affect the overall energy consumption, comparing to the energy consumed by the electronic components and also signal processing mechanism in the transmitter, receiver, and also the relay amplifiers. This motivates us to introduce a new layer of public transport to use as a data carrier, especially for those data services, e.g., file transfer or backup which are of delay-tolerant natures. We further elaborate on energy consumption for traditional networks and vehicular networks to validate our model to save energy consumption using vehicles.

Energy Consumption Model for Traditional Network

In a traditional network, while sending data, data will be uploaded to the core network and forwarded according to the principle of TCP/IP and on the other side, it will be downloaded from the core network. If there are n bits to send, energy consumption depends upon the energy consumed by nodes at both ends to download and upload on sending and receiving sides and the number of network equipment used such as routers/hops used in between till the final destination. The delay value depends upon the bandwidth used and the storage capacity available to carry data.

$$E_{Nodes} = \max(\frac{n}{B_{up1}}, \frac{n}{B_{down2}}(\Delta P_{Node1} + \Delta P_{Node2})) \tag{5.4}$$

where E_{Nodes} is the energy consumed by nodes to upload and download. B_{up1} and B_{down2} are the upload and download bandwidth of the sending and receiving node. ΔP_{Node1} is the variation in power usage by a node during the data transfer.

$$E_{bit} = \frac{P_{max}}{B} \tag{5.5}$$

where n is to be defined as the number of bits transferred. B is its maximum bandwidth used and P_{max} is the maximum power drawn by a device. We will also consider the incremental energy consumption E_{inc} for transferring one bit to model the energy consumption of network equipment.

$$E_{inc} = n * E_{bit} \tag{5.6}$$

Furthermore, with the total incremental energy consumption of transmission to be considered as the sum of energy consumption by nodes and the incremental consumption per bit. Where k is the number of network equipment used during the transfer. In our case study, we assume that there are 3 switches, 2 core routers and 2 edge routers in between both locations. Energy consumption can be calculated from Eq. 5.7 as per the incremental energy and energy consumption by nodes. Uploading and downloading bandwidth is 0.1 Mbits/s and 1 Mbits/s for each node to upload and download data onto internet.

$$C_E = E_{Nodes} + \sum_{i=1}^{k} E_{inc1} \tag{5.7}$$

Energy Consumption Model for Public Transport Network

This option considers data communication to offload data onto scheduled public vehicles as per their nature such as delay tolerant or non-real-time. The extra storage room can be installed onto a bus and data can be offloaded from the network infrastructure towards the transport infrastructure. We first consider the energy of nodes to upload and download data onto a vehicle. In this option, we consider different parameters such as data size, location, and the possibility to visit that region within the given stipulated time, and the urgency of data transfer.

$$E_{Nodes} = \max(\frac{n}{b_{up1}}, \frac{n}{b_{down2}}(\Delta p_{Node1} + \Delta p_{Node2})) \tag{5}$$

where b_{up1} and b_{down2} are the upload and download bandwidth of the sending and receiving nodes. Δp_{Node1} is the variation in power usage of a node during transport. We will use wifi-direct as an interface for uploading and downloading data. Much like routing within the Internet, a data package may be sent to various routers/hops until it is forwarded to the receiver directly. Using public transport, the distance between the sender and the receiver affects the time taken to deliver that packet. Also, the longer the trip, the probabilities are higher that more vehicles will be used as relay nodes. However, the energy consumption of a vehicle also depends upon the vehicle types as per the fuel economy, vehicle weight, and distance traveled. For this case study, the bandwidth to upload and download data is considered as 24 Mbits/s for wifi-direct. The approximate weight of a hard-disk of 2TB and fuel consumption of bus is 0.95 and $\alpha_{diesel} = 38,290,237.52 J/L$ [177]

$$E_{travel} = \alpha_{fuel} \times W_{package} \times \sum_{i=1}^{k} E_{loading} \tag{5.8}$$

where α_{fuel} is to be considered as a constant value which converts fuel volume into liters and Joules

$$E_{loading} = \frac{d_i}{fueleconomy_i \times W_{vehicleload_i}} \tag{5.9}$$

Finally, the total energy consumption of uploading n bits onto the vehicle is:

$$C_E = E_{Nodes} + E_{travel} \tag{5.10}$$

5.3.2 Delay Model

The delay model is defined as the time taken for a packet to get delivered from the source until the destination. The packet remains in the queue and there are many other factors such as relay nodes, availability of the network, signals, etc which decrease or increase the delay in delivering a packet to the destination. We will be calculating delay for both networks as below:

Delay Model for Traditional Network

To calculate delay for the traditional network, it depends upon the data volume of the packets and the distance. The distance comprises all the intermediated nodes and devices used in between for communication. We assume that V is the volume of the packet and L_{packet} is the length of the packet, the number of packets delivered N_{total} can be calculated as

$$N_{total} = \frac{V}{L_{packet}} \tag{5.11}$$

There are in total N number of nodes in between source and destination. The total delay can be estimated as the sum of processing delay (D_{proc}), waiting time delay $(D_{waiting})$, Transmission delay(D_{trans}) for all nodes in between and defined as:

$$D_{trad} = N \times D_{packet} + (N_{total} - 1) \times (D_{proc} + D_{waiting} + D_{trans}) \tag{5.12}$$

However, in some cases of dedicated links, if there is not any packet on the waiting list, then waiting time will turn out to be zero. At the same time, packets will be processed parallelly and processing time will be negligible. In this case, the delay will be

$$D_{trad} = N \times D_{packet} + (N_{total} - 1) \times D_{trans} \tag{5.13}$$

Transmission delay is the delay being calculated as per the delay in uploading/downloading as per bandwidth rate and the volume of the packet and can be defined as:

$$D_{trans} = \frac{V}{B} \tag{5.14}$$

The delay for data volume in the traditional network can be calculated as

$$D_{trad} = N \times D_{packet} + (N_{total} - 1) \times \frac{V}{B} \tag{5.15}$$

Delay Model for Public Transport Network

The deadline for delay D_{max} is to be defined as the maximum delivery time of a packet from the source until destination. The distance between source and destination can be measured by Euclid distance as $d = ||b - b_{st}||$, where b is the bus on that route, and b_{st} is the access point for data uploading/downloading data. In the case of the public transport network, the total delay depends upon two major factors: first travel time (TT) between source and destination and data offloading time $(T_{offloading})$ and can be defined as:

$$D_{PT} = TT + T_{offloading} \tag{5.16}$$

As define already, the distance is measured as d, v is the average velocity of the bus, then travel time (TT) is defined as:

$$TT = \frac{d}{v} \tag{5.17}$$

The data offloading time $(T_{offloading})$ depends upon the volume of data (V) and bandwidth used B_{BS} at each bus stop and available buses on that route N_{bus}.

$$T_{offloading} = \frac{V}{N_{bus} \times B_{BS}} \tag{5.18}$$

The total delay in public transport can be defined as

$$D_{PT} = \frac{d}{v} + \frac{V}{N_{bus} \times B_{BS}} \tag{5.19}$$

5.4 Case Study I: Auckland Public Transport

Same as the previous chapters, We will be using the Auckland Transport network here again to validate our model to minimise energy consumption. We are introducing a new layer of delay-tolerant networks, especially using public transport networks such as buses. We present the case study of the Auckland Physical Things map with all

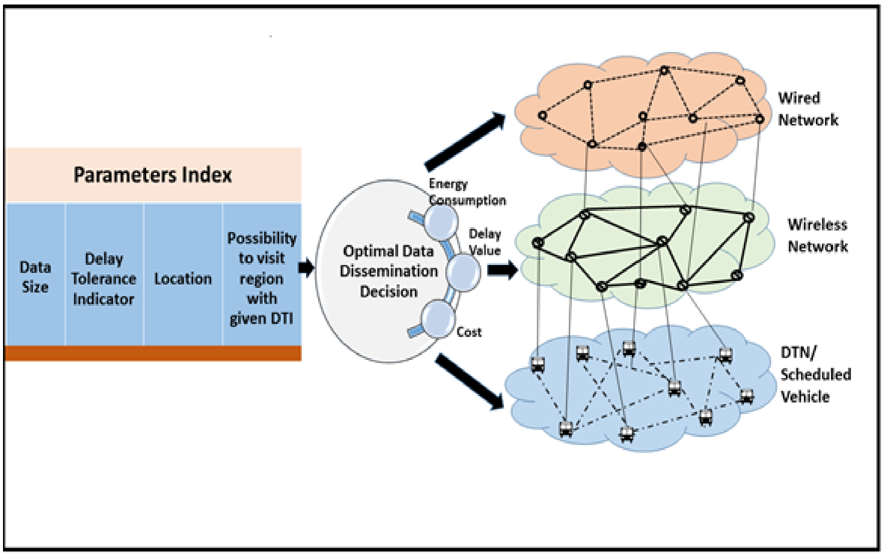

Figure 5.2: Energy-Efficient Data dissemination among Three Layers

real objects for evaluation. Auckland is the larger city in New Zealand and its public transport system is well known for its reputation, punctuality, synchronized timetables, efficiency, frequency, and high quality of service and innovation. Auckland Transport (AT) works closely with Auckland Council and the NZ Transport Agency (NZTA) on all the prospective plans. We will consider scheduling buses to carry data from one place to another place. If data is not urgent, the user will request to scheduled bus/shuttle to carry data and deliver it to the destination. For example, an organization sends every day large data from one location to another location in terms of backup, information sharing, content delivery, etc., which is being sent through network infrastructure (wired/wireless network). There is also public transport available between both places every 30 minutes and best utilize its existing transport infrastructure as a part of data communication in a more energy-efficient manner.

An SDC controller will make a forwarding decision as per the user's profile and the sustainable options available. The Software-Defined Connectivity layer will provide

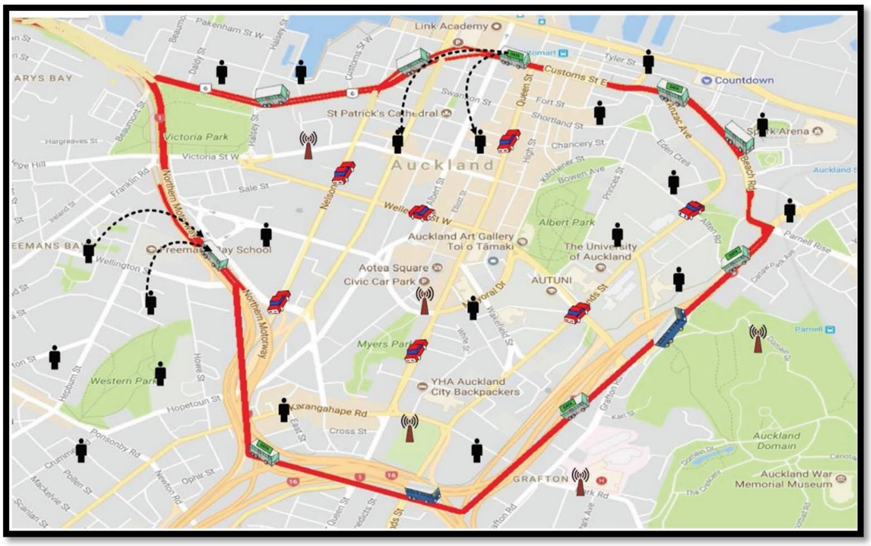

Figure 5.3: Auckland Map Data Allocation

connectivity among users and all scheduled buses to carry data from one place to deliver it to the sink node as per their demands and objectives. We aim to validate that the SDN controller can make a reliable and energy-efficient data forwarding decision. We will further discuss both data dissemination decisions based upon AT dataset.

As far as we are sending data, more network equipment is involved and each one of the devices consumes energy to forward packets. Our main motive is to minimize energy consumption while sending data from one place to another place either using a traditional network or public transport network.

5.4.1 Data Dissemination using Internet

In the case of data dissemination using the internet, this is a traditional way of sending data either using a wired or wireless network. We have picked a few locations in Auckland to send data using the traditional network from one place to another as shown in Fig. 5.3. In the first case, we assume that the source is in Auckland CBD and wants to send data to Henderson with 17km distance. The controller follows the forwarding process and chooses this option if data is non-delay tolerant or delay-sensitive. We discussed in the previous chapter, network selection will be based upon different attributes and criteria and one of the most important criteria is data type i.e. delay tolerant or delay-sensitive. Data gets uploaded onto the conventional network and all packets get forwarded through regular network equipment such as LAN switches, Core, and Edge routers. Energy consumption can be calculated from Eq. 5.7, which is the sum of energy consumption by nodes and incremental energy used. Uploading bandwidth is 0.1 Mbits/s and downloading bandwidth is 1 Mbits/s for each node in sending data through the internet [176]. In such a way, we can compare with the public transport network to analyze the energy-efficient data dissemination option.

5.4.2 Data Dissemination using Public Transport

This option considers data dissemination using scheduled public vehicles as per their nature of data such as delay tolerant or non-real-time. The SDC controller provides a programmatic interface of existing real objects to the network. It implements management tasks such as the availability of the bus within the stipulated time and it provides connectivity options as per their demands and objectives. In this option, we consider different parameters such as data size, location, and the possibility to visit that region within the given stipulated time, and the urgency of data transfer. We first consider the energy of nodes to upload and download data onto the vehicle.

We will use 1EEE 802.11ay [64] as an interface for uploading and downloading data. The energy consumption of a vehicle also depends upon the vehicle types as per the fuel economy, vehicle weight, and distance traveled. The approximate weight of a hard disk of 2TB and fuel consumption of a bus is 0.95 and $\alpha_diesel = 38,290,237.52 J/L$. To elaborate more, let us consider a bus service from Auckland to Henderson, which is about 17 km far from Auckland central. There are three possible public transport services for this route such as bus no 133, 134, and the WEST train service. Let us take details of one possible route 133 to see how much data it can deliver. The frequency of this bus is every 15 minutes and covers 34 total stops. The GPS report of bus 133 is provided in Table II, which states bus frequency, stops covered, route pattern, etc. This GPS report helps us to take the selection of buses as per the profile of users and their demands are given in the flow table. Many Auckland bus stops are equipped with AT hop WIFI and data can be easily offloaded onto these buses. These buses operate from 5.50 am until 11.55 pm for 7 days a week. The data volume and distance traveled are two major factors to validate the energy consumption model. We will calculate energy consumption in both cases and can analyze the energy-efficient option as per the different demands of users.

5.4.3 Result Analysis

We do sensitivity analysis in between traditional ways of communication and our solution (Scheduled vehicle) to get results that which one is the better technique. We will consider energy consumption, delay, and throughput metrics to evaluate the performance of our model.

Energy Consumption

Energy consumption is calculated as the amount of energy spent on transmission and scanning. We show that energy consumption depends upon the data volume and distance to forward packets. Results from Fig. 5.4 depict the energy consumption for all the locations as per the distance covered. This figure ultimately shows that if data is delay tolerant, we can utilize public transport all over Auckland to disseminate data in an energy-efficient manner. While considering the same locations to send data of we to increase the data volume and consider both options for data dissemination. Fig. 5.5

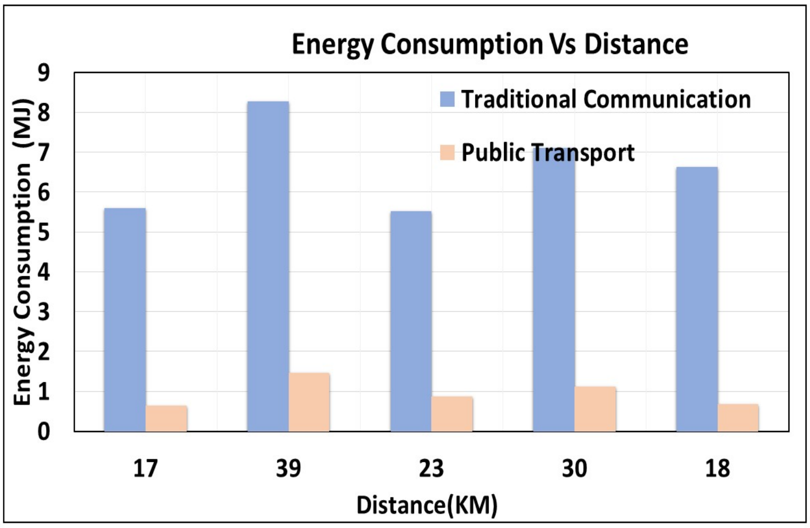

Figure 5.4: Energy Consumption Vs Distance

illustrates that public transport is still a viable option to consider as per the data volume. In the case of 64TB data to be sent, energy consumption is 207.06 MJ in the case of a traditional network and 76.33 MJ for the public transport network.

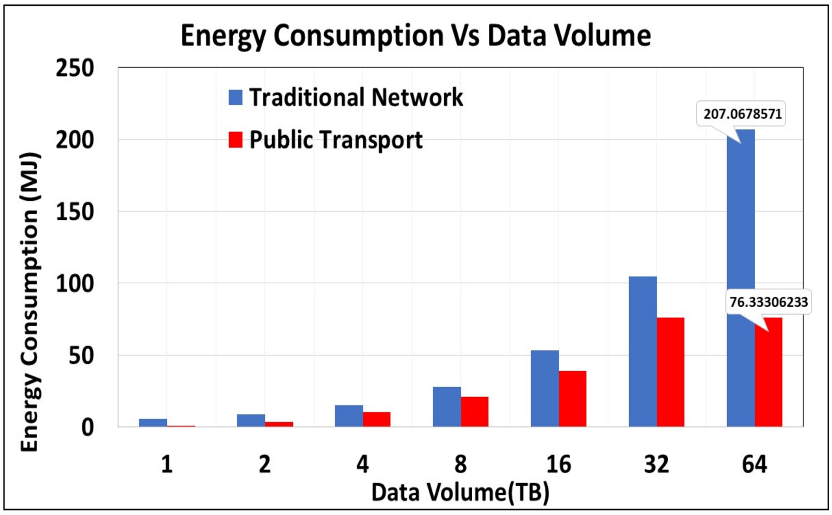

Figure 5.5: Energy Consumption Vs Data Volume

These results ultimately show that if data is delay tolerant, we can utilize public transport all over Auckland to disseminate data in an energy-efficient manner. While considering the same locations to send data of we to increase the data volume and

Auckland CBD → Henderson	Total Energy (Internet) 2.267857142(MJ)	Total Energy (Public Transport) 0.161 (MJ)
L3 switches	6	N/A
Edge Routers	2	N/A
Core routers	5	N/A
ΔP_{Node}	20 W	N/A
B_{up}	1 Mb/s	24 Mb/s
B_{down}	0.1 Mb/s	24 Mb/s
Distance	17km	17 km
Weight	N/A	0.95(2TB)
α_{diesel}	N/A	38,290,237.52 J/L

Table 5.1: Data forwarded through both networks

consider both options for data dissemination. Figure 5 6 illustrates that public transport is still a viable option to consider as per the data volume. In the case of 64TB data to be sent, energy consumption is 207.06 MJ in the case of a traditional network and 76.33 MJ for the public transport network.

Delay Value

Delay is to be encountered by a packet to deliver it to the destination. The delay factor also depends upon distance and data volume as well. As discussed in the delay model, we will calculate the delay value for both cases for data forwarding. We increase the data volume and can get the outcome of delay value as shown in Fig. 5.6. Delay values keep on increasing as per the data volume and still, the value is less if using public transport in comparison with the internet network. Moreover, travel time is also considered as per the distance traveled. In the next option shown in Fig. 5.7, we consider delay value as per distance traveled. In the case of the internet, more network equipment will be used and delays depending upon the distance as well. Scheduled bus journey delay time also varies as per the distance to the destination. However, it remains consistent in the

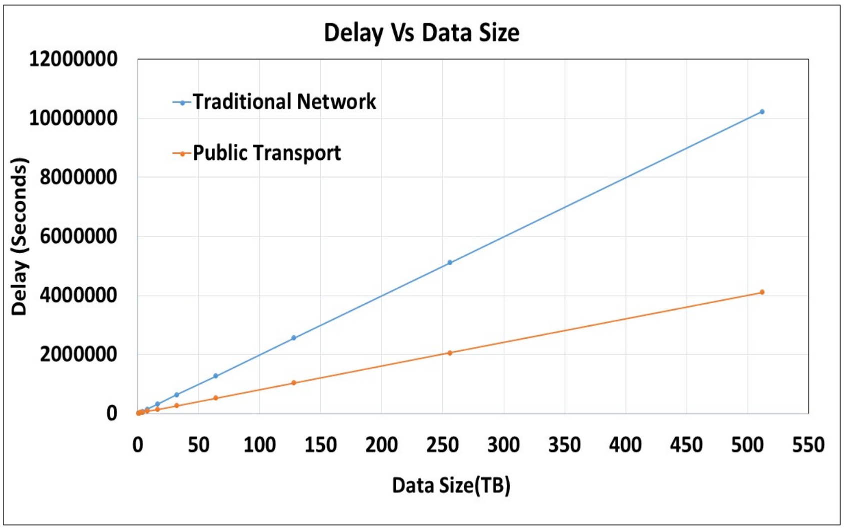

Figure 5.6: Delay Value Vs Data Volume

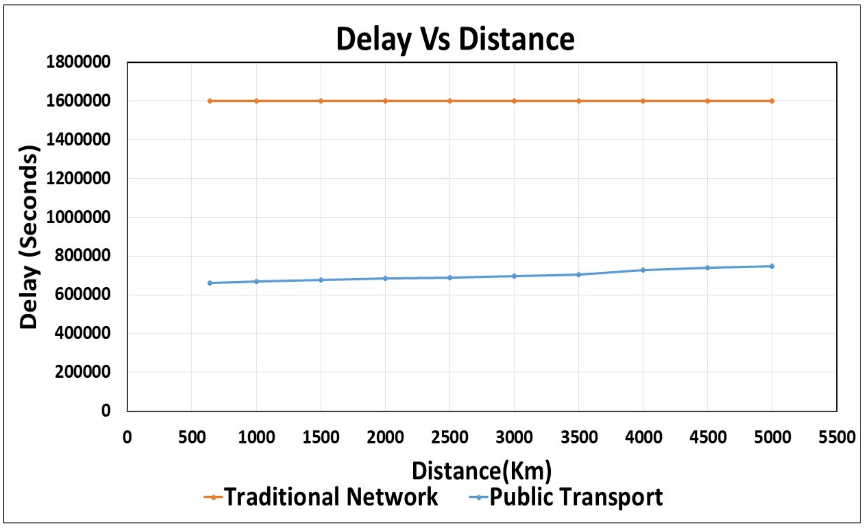

Figure 5.7: Delay Value Vs Distance

case of the Internet infrastructure as per the distance covered.

Carbon Emission

We all know the data transmission process also consumes fuel and electricity and ultimately emits some carbon into the atmosphere. Many factors affect the percentage of carbon emission while sending data through the core network and PTDD. As defined in Eq. 5.8, the energy consumption also depends upon the weight of the disk. If we put extra weight onto our buses that leads to some extra carbon emission as shown in Fig. 5.8. In such way, energy consumption leads to more carbon emission into the atmosphere. The CO_2 emission increases by 1.22% for 100 kg weight and 100 kilometers distance traveled.

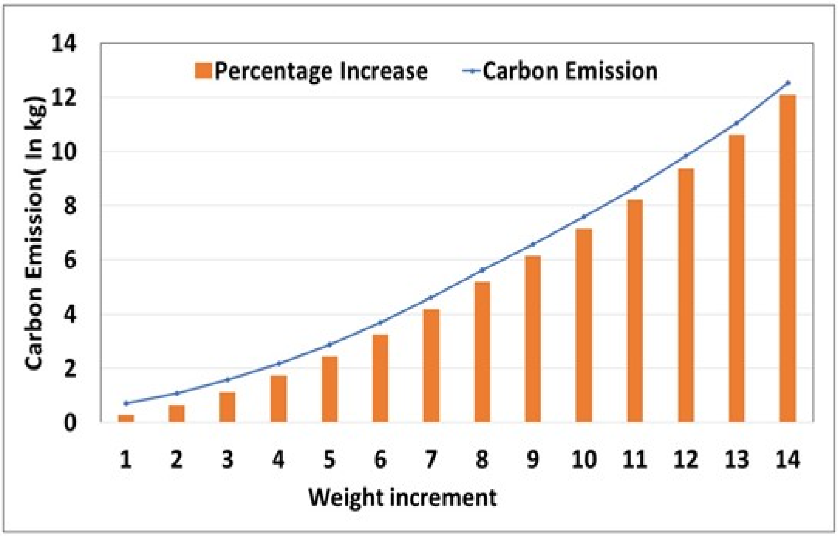

Figure 5.8: Carbon Emission with Weight Increment

Throughput Analysis

Next, after assessing energy consumption, delay value, and carbon emission, we analysed that public transport is an energy-efficient option for delay-tolerant data dissemination. However, it is important to know that how much data can be offloaded onto buses when it stops at any bus stop. Therefore, our emphasis to measure the transmission performance for data objects at one bus stop since the overall transmission performance practically depends on data transfers from all bus stops to the buses. The ideal data transmission performance is being calculated as the throughput value. Throughput is defined as the amount of data transferred on the bus concerning time and denoted as X. Where Ps is the packet size and T is defined as operation time. The throughput during operation is calculated as

$$X = (p_s) \times 8/T(s) \tag{5.20}$$

We have realized that there are a different number of bus services during a different time of the day. So, the ideal transmission performance varies as per the number of buses and their stopping time at any bus stop. As shown in Fig. 5.9 and Fig. 5.10 , the stopping time increases, the same way the amount of data offloaded, and throughput vary as per the increment in the number of vehicles/buses.

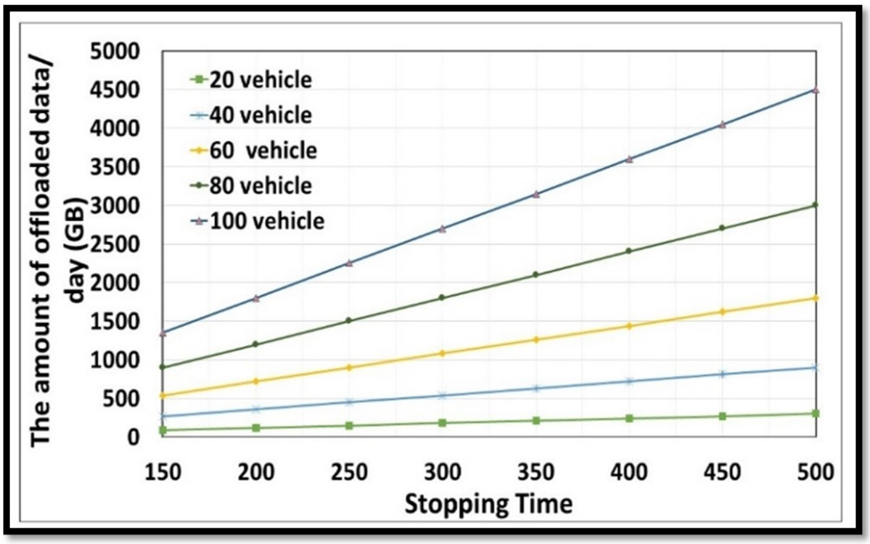

Figure 5.9: Data Offloaded in a Day as Per Stopping Time

If a bus stops for 500 seconds, for a total of 60 buses, the offloading capacity of local storage is 64.8 GB/day with an effective throughput of 22.03 MB/s. In addition to it, the transmission performance highly depends on stoppage time at a bus stop and the number of buses in a day. Fig. 5.11 shows the transmission performance of each network for different data rates. We have considered that public transport will be using IEEE 802.11ac as a network interface for data allocation. However, For comparisons, we use the bandwidth of 512 Mbps and 1 Gbps in the traditional network to have an actual difference with varying bandwidth for 50 buses. The outcome demonstrates that our proposed public transport network outperforms the traditional core network.

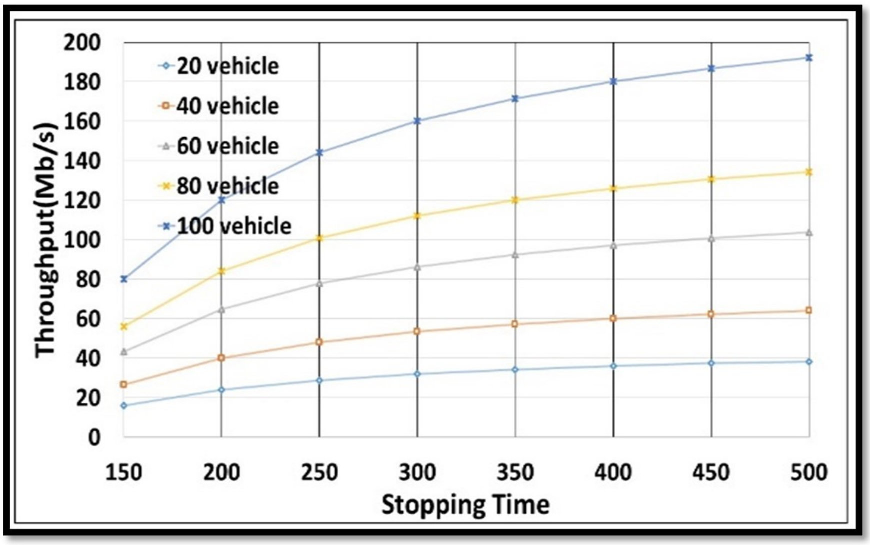

Figure 5.10: Throughput as per Operation Time

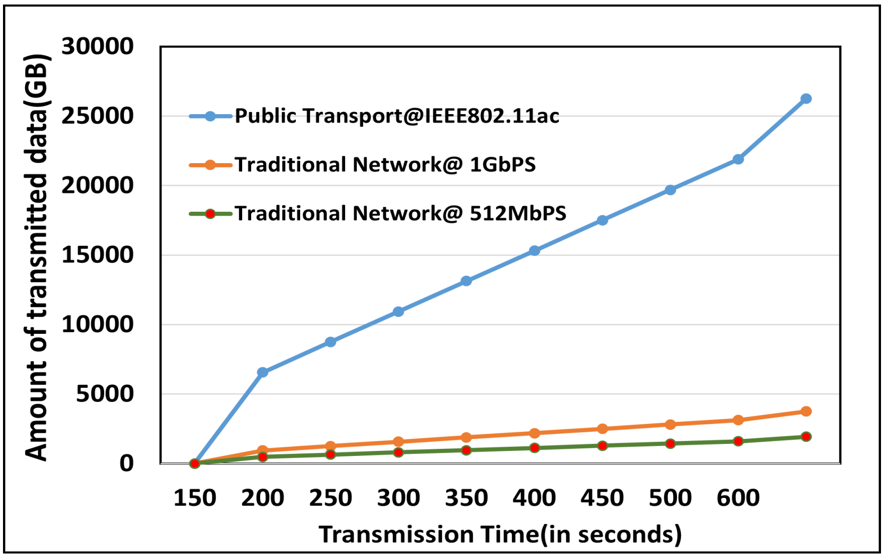

Figure 5.11: Transmission performance

5.5 Case Study II- Energy Consumption Optimisation

Our main objective is to minimize the energy consumption of sending data from one place to another place while using traditional networks or public vehicles. We are going to formulate our problem considering two factors such as data volume and distance traveled with two perspectives. First, we want to minimize the energy consumption to disseminate data while using scheduled vehicles as a transmission mode.

5.5.1 Problem Formulation

We are using a network flow model to formulate our problem to find a more sustainable approach in the heterogeneous network. Given is a network topology modeled as graph $G = (V, E)$ comprising a set of nodes V and links E. The graph may be viewed as a street mesh, where links represent streets and nodes represent crossroads with $m \times n$ mesh directed network. Here, we are considering two types of networks, one is Internet Network and another one is Vehicular Network.

Multi-Commodity flow problem

We use a network flow model to formulate our problem to find more sustainable approach in the heterogeneous network. Given that a network $G = (N, E)$, where N = set of nodes = (i, j, k, l, m, n), E = set of links =$(i, j), (i, k), (l, m)$ nodes and a collection of E edges, where each edge is a pair of nodes from N. In the context of our problem, we consider a set of two commodities $d \in D$ such that $d = I, V$. We can define a primary network (internet network) flow as $G^I = (N^I, E^I)$ and secondary network as $G^V = (N^V, E^V)$ for a vehicular network. let $R = \{(s_i, t_i, b_i)\}$ be a set of requirements. For each edge $(i, j) \in E$. $s_i \epsilon N$ is data source and $t_i \epsilon N$ is destination data center for commodity b^i. Thus, given:

1. *the two network topologies:* $G^I = (N^I, E^I)$ *and* $G^V = (N^V, E^V)$*, such that each of the pair of* $E = (i, j), (j, k)$ *are the set of links connecting the nodes i,j and j,k respectively,* $N = (i, j, ..., n)$ *are nodes in a network* $N(s, t)$ *are the source and terminal*

2. *Demand* $(b^I + b^V) = b^i$ *between each source and terminal, where* b^I *is the demand for internet network and* b^V *is the demand for the vehicular network.*

3. *The total amount of flow produced at each node:* F_{ijd} *across each of the arc* (i, j)

4. *Energy consumption between* C_{ijd} *for both of the commodities*

5. *In addition, there is a fixed charge* $f_{i,j}$ *for the use of each arc* (i, j)

6. $U_{i,j,d}$ *is the capacity of both commodities*

7. *Let* $y_{ij} = 1$ *if vehicular network will be used*

   $y_{ij} = 0$ *if internet network will be used*

8. *T is to be defined as max time to get delivered the data and* $t_{i,j}$ *is a total delayed time in the vehicular network*

Objective: To minimize

$$\sum_{i,j \in N} \sum_{d \in D} C_{ijd} F_{ijd} + \sum_{i,j \in N} f_{ij} y_{ij} \tag{5.21}$$

Constraint: Subject to

$$\sum_{i,j \in N} F_{ijd} - \sum_{i,j \in N} F_{jid} = b_{id}; \qquad \forall (i, j) \in N(s, t)\ , \forall d \in D \tag{5.22}$$

$$\sum_{i,j \in N: n==t} b_{id} - \sum_{i,j \in N, n==s} b_{di} = 0; \qquad \forall n \in N(s, t) : n \neq s, n \neq t \tag{5.23}$$

$$\sum_{i,j \in N: n==t} b_{id} - \sum_{i,j \in N, n==s} b_{di} = -1, \qquad \forall n \in N(s, t) : n = s \tag{5.24}$$

$$\sum_{i,j \in N: n==t} b_{id} - \sum_{i,j \in N, n==s} b_{di} = 1, \qquad \forall n \in N(s, t) : n = t \tag{5.25}$$

$$F_{ijd} \leq U_{ijd}, \qquad \forall \quad i, j \in N(s, t) \quad , \forall d \in D \tag{5.26}$$

$$F_{ijd} \geq 0, \qquad \forall i, j \in N(s, t) \quad , \forall d \in D \tag{5.27}$$

$$y_{ij} \in \{0, 1\} \tag{5.28}$$

$$\sum_{i,j \in N} F_{i,j} t_{i,j} \leq T \tag{5.29}$$

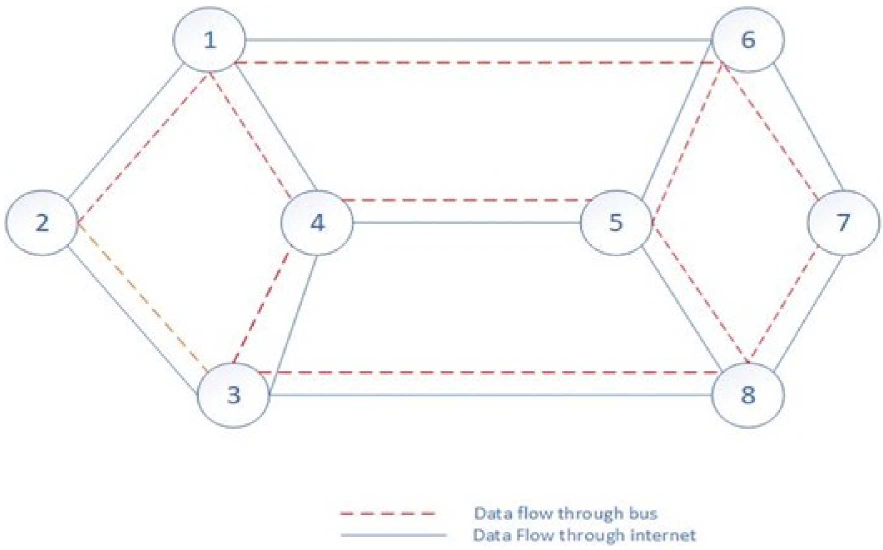

Figure 5.12: Network flow Problem from Source to Terminal

Equation 5.21 is the objective function to minimize the consumption among both commodity and fixed travel consumption of the vehicle. Eq 5.22 defines the flow conservation demand constraint of each node. Eq (5.23, 5.24, 5.25) define the network flow constraints according to source and sink node for both networks, where s and t are source and terminal, For each node $i, i = 1, 2, ..., n$, an (integer) number b_i is given, representing the amount of flow produced (if $b_i < 0$) or consumed (if $b_i > 0$) at i. The nodes that produce flow are sometimes referred to as a source, and b_i as supply. Nodes that consume flow are called sinks, and b_i as demand. If $b_i = 0$, node i do not consume nor produce flow, i.e., it is a transit node. Eq 5.26 illustrates that flows on each link is always less than link capacity. Eq 5.27 states that network flow is a non-negative value. Eq 5.28 is the decision variable for which network will be chosen. Eq 5.29 describes that the traversed time delay of each edge should not exceed the maximum delivered time. We solved our problem using Algorithm 4 to solve the energy optimisation problem by transferring a huge range of data volume in network $N(s,t)$ from source node s to the terminal node t considering two commodities. We used IBM ILOG CPLEX Optimization studio solver to find the optimal network solution as per the user's demands.

Algorithm 4: Minimum consumption multi-commodity flow

Input: A graph $G = (N, E)$, and set of requirements $R = \{(s_i, t_i, b_i)\}$
Output: Set of paths that meet the requirements

$G^V \leftarrow G^I \leftarrow G$, and $P = \phi$
while $|P| < |R|$ **do**
    for $r_i \in R$ **do**
        $p_{id} = minimum\_consumption\_flow(G^V, s_i, t_i, b_{id})$
        if $p_i == \phi$ **then**
            $p_{id} = minimum\_consumption\_flow(G^I, s_i, t_i, b_{id})$
            for $(eachedge(i, j), U_{ijd}) \in p_{id}$ **do**
                if $U_{ijd} > Available\_Capacity\_in\_G^V$ **then**
                    Cost increment in G^V and G^I
                    for $p \in P$ **do**
                        if $(i, j) \in p$ **then**
                            $P \leftarrow P - p$
                            Return the capacity used by p to G^V
                        end if
                    end for
                end if
            end for
        else
            Reduce the capacity of edges in p_{id} from G^V, $P \leftarrow P \cup p_{id}$
        end if
    end for
end while
return P

5.5.2 Energy-Efficient Network mode selection

For data allocation onto buses, we will be using a multi-commodity flow problem for the best optimal solution to traverse data over a network while considering the requirements of each user as per their profile.

By using a multi-commodity flow problem and energy consumption model defined in Section 5.3, we have identified energy consumption for a different set of commodities defined for non-urgent data and looking forward to optimal network selection for data allocation. Algorithm 5 outlines the network selection procedure among both networks with minimum energy consumption. The dataset in Table 5.2 outlines the energy

Algorithm 5: Network Selection Procedure

Input: Graphs $G^I = (N^I, E^I)$, $G^V = (N^V, E^V)$ and set of requirements $R = \{(b_i, C_{i,j}, U_{i,j})\}$

Output: Network Selection with min energy consumption

```
C_E^I ← f(G^I, R)
C_E^V ← Min_consumption_multi_commodity_flow (G^V, R)
for r_i ∈ R do
    if C_E^I > C_E^V then
        mode_i = Public Transport Network
    else
        mode_i = Conventional Network
    end if
end for
return mode
```

consumption while using both networks on each link defined in Fig. 5.12.

From	To	Lan L3 Switches	Edge routers	Core routers	Up BW	Down BW	Energy Internet (MJ/TB)	Energy PT (MJ/TB)
1	2	9	2	15	0.1	0.1	6.99	0.56
1	4	3	2	14	0.1	10.0	5.03	1.12
2	3	8	2	14	1.0	1.0	6.63	1.30
3	8	8	2	3	1.0	1.0	6.15	0.75
3	4	6	2	3	1.0	1.0	5.51	0.64
4	5	6	2	5	0.1	1.0	5.59	0.79
5	6	11	2	3	1.0	1.0	7.11	0.60
5	8	9	2	6	1.0	10.0	6.60	0.90
7	8	8	2	6	0.1	0.1	6.28	0.60
6	7	7	2	7	1.0	1.0	6.00	1.67
1	8	13	2	7	0.1	0.1	8.23	1.78
2	8	11	2	5	1.0	1.0	6.41	1.23
4	8	13	2	14	0.1	0.1	6.60	0.97
1	6	8	2	9	1.0	10.0	7.62	1.41
6	8	9	2	6	0.1	0.1	5.7	1.21
3	6	13	2	15	1.0	1.0	2.215	1.64

Table 5.2: Energy Consumption to transfer 1 TB on each link

As shown in Fig. 5.13, proves that our model outperforms traditional network communication in terms of energy efficiency and existing public transport can be efficiently used for data dissemination. The traditional network consumes more energy in comparison with PTDD. The total energy consumed by traditional network is 35MJ/TB and by

PTDD is 6.6MJ/Tb. Therefore, with the optimal network mode selection, we can save up to 54% of the energy consumed in data transmission.

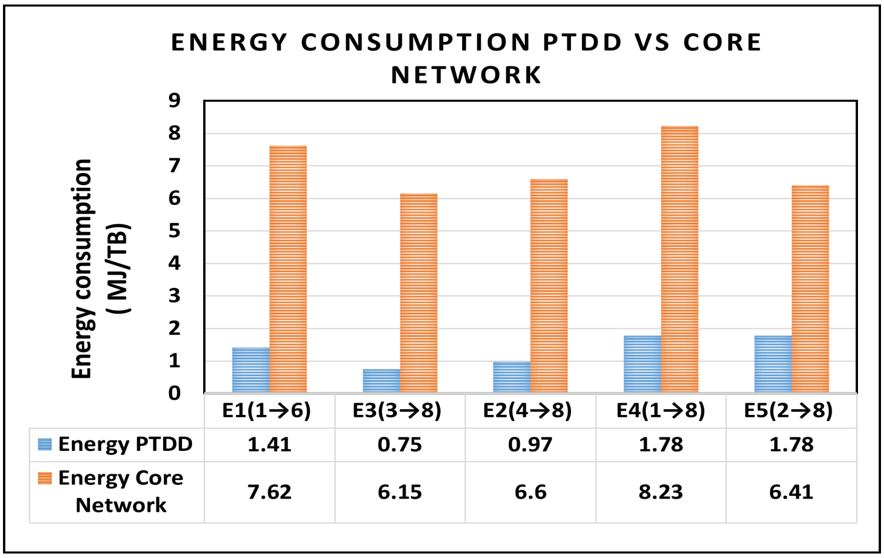

Figure 5.13: Energy Consumption Comparison between PTDD and Core Network

5.6 Case Study III: Energy-Efficient Data Dissemination

Moving further, as discussed, in the previous chapter, data gets allocated to buses at each bus stop. Each bust arrival time and stay time helps to analyze offloading efficiency at each stop for different PLE factors. Our goal is to minimize energy consumption while using public transport as a data carrier. As shown below in diagram Fig. 5.14, the source data center accumulates all the data from nearby user devices and cache it until an optimal bus is not available for the destination route. At each bus stop, RSU has been deployed to offload data onto buses and these buses carry data until the destination bus stop and upload onto the destination bus stop.

In the previous case study, we used the multi-commodity flow problem to handle different demands and allocating data either on vehicle or internet network. In this

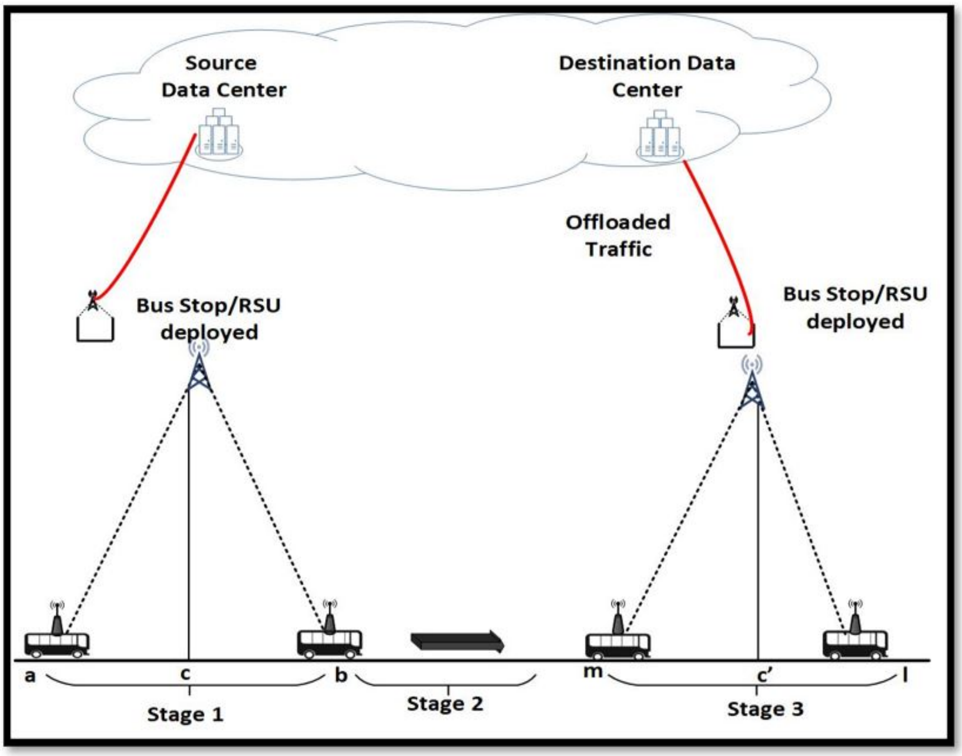

Figure 5.14: Proposed scheme for the problem

case study, we will be taking different demands from the data center (DC) to allocate data onto buses as per their maximum capacity to carry data until destination while minimizing energy consumption. We will be using the Capacitated Vehicle Routing Problem (CVRP) to minimize energy consumption while using public transport as a data carrier.

In our model, all demands are being fetched from DC by the controller and being allocated to the appropriate bus going on a trip in the direction of the destination location. Note that, data offloading/uploading is possible when each bus stops at bus-stop, therefore the transmission range is expected to be limited for data offloading onto these buses. The whole transmission procedure and energy consumption is being calculated in 3 stages.

Stage 1: RSU to Bus transmission: When the bus stops at the parent stop or source data center, data gets allocated onto the bus within the transmission range. As shown in

Figure 5 11, a and b are the earliest and final points for stage 1 . Point c denotes the central projection when the bus stops at the bus stop.

Stage 2: Stable State: In stage 2, the bus will carry data as per demands on its fixed route and does not consume any extra energy due to extra weight and will be negligible

Stage 3: Bus- RSU transmission: In stage 3, the bus reaches the destination spot and uploads data onto the bus stop. l and m are the initial and final points of this stage, c' is the vertical projection of RSU deployed at the destination bus stop. We will minimize energy consumption by offloading data onto the fixed bus with a fixed capacity to carry data and finding the optimal solution.

5.6.1 Problem Definition

We will have to consider a DC, where data gets accumulated and there is a bus stop near DC to offload data onto buses. . In other words, there and n number of demands being fulfilled by a DC, and a nearby stop is a depot to start the bus journey and returning to the same bus stop after finishing its route. B is the set of buses $(B = B_1, ...B_N)$, C_B is the capacity of the bus, D is the deadline for the message delivery which also considers the number of trips being taken by a bus. Each DC has different demands d_i for different locations. We are defining our problem into a graph $G(V, E)$, where $V = 0, 1, 2...n$ is a set of all nodes of the graph and E is the set of edges $(i, j)...(I, j)\epsilon N$. Arc (i, j) represents the path from node i to node j. The energy consumption (E_{ij}) is being calculated for each bus to carry data from the source until the destination. The minimum number of buses required to fulfill all the demands is $\frac{\sum_{i=1}^{n} d_i}{C_B}$. The controller will be assigning demands to each bus as per the destination location. A CVRP can be formulated as follows:

Objective: To minimize

$$\sum_{b\epsilon B}\sum_{i=1}^{n}\sum_{j=1}^{n} E_{ij}X_{ijb} \tag{5.30}$$

which minimize the total energy consumption by buses. There are various constraints subjected to this function and defined below:

Subjected to

$$\sum_{i=1, i\neq j}^{n}\sum_{b\epsilon B} X_{bij} = 1 \qquad \forall j = 1, ...n \tag{5.31}$$

$$\sum_{j=1}^{n} X_{b,0,j} = 1 \qquad \forall\ b\epsilon(B_1, B_2, ...B_n) \tag{5.32}$$

$$\sum_{i=1, i\neq j}^{n} X_{bij} = \sum_{i=1}^{n} X_{bij} \qquad \forall j = 1, ...n, \quad b\epsilon(B_1, B_2, ...B_n) \tag{5.33}$$

$$\sum_{i=1}^{n}\sum_{j=1, i\neq j}^{n} d_j X_{bij} \leq C_B \qquad \forall b\epsilon(B_1, B_2, ...B_n) \tag{5.34}$$

$$\sum_{b=B_1}^{B_n}\sum_{i\epsilon T}\sum_{j\epsilon T, i\neq j} X_{bij} \leq |T| - 1 \qquad \forall T \subseteq (1, ...n) \tag{5.35}$$

$$X_{bij}\epsilon(0,1) \qquad \forall b\epsilon(B_1, B_2, ...B_n); i, j = (1, ...n) \tag{5.36}$$

Where X_{ijb} the binary variable defines a set of buses $b \in (B_1, B_2 \ldots B_n)$ that traverses an arc (i, j). The objective function defined in Eq. 5.30 minimizes the energy consumption cost. Constraint 5.31 are the degree constraints and confirm that each demand will be fulfilled by available bus. Each bus starts its trip from the parent stop, where data gets offloaded, delivers data at the destination, and finishes the trip at the same stop as shown in constraint 5.33. Constraint 5.34 defines the maximum capacity of the bus to carry data. All the demands of DC are being fulfilled by available buses of the day. Constraint 5.35 defines that as per defined time, there are no cycles disconnected to the parent stop. The definition domains of the variables are being described in the constraint 5.36. We used Algorithm 6 for energy-efficient data dissemination using selected buses.

Algorithm 6: Capacitated Vehicle Routing Problem

Input: Graphs $G = (V, E)$, Demands=d_i, Capacity=C_B,$P \leftarrow \{\phi\}$, $Sol \leftarrow \{\phi\}$
Output: Energy-Efficient data dissemination with selected buses
Initialization; i=0 (Depot), Bus=B_i
while $|P| \neq N$ **do**
  $|P| \leftarrow P\cup$ obtained sequence from nearset bus stop randomly
  for $V \leftarrow 1....n$ **do**
    $Sol \leftarrow Sol\cup$ Selected route traversing each bus-stop
    if $d_i > C_B$ **then**
      Wait(B, V);   Increment $B = B_i + 1$;
    else
      Upload (B, V) Assign demand $d_i \in B$
      $C_B = C_B - d_i$
    end if
  end for
end while
return Sol

5.6.2 Numerical Analysis

We conduct a numerical example to allocate different demands being generated from DC on buses to carry data until destination while minimizing energy consumption. We are considering 16 demands generated randomly from different bus stops to deliver their data carried by bus.

As shown in Fig. 5.15, There are many bus-stops around and demands have been allocated to DC for data allocation onto the suitable bus. The controller will make an energy-efficient decision based upon equation 36. DC is the central deport where the bus starts and finishes its journey. As per Table 5.3, different data demands are being generated for data being delivered from the depot to the destination stop. The controller identifies 4 buses: B1, B2, B3, and B4 to fulfill all demands with an energy-efficient solution. The total capacity of each bus is 150TB to carry. The distance to each bus stop has been given from the central depot or source bus stop.

The demands must not exceed the maximum capacity of the bus. We use CVRP instances from the past and we solve it using the Cplex optimization solver. We have

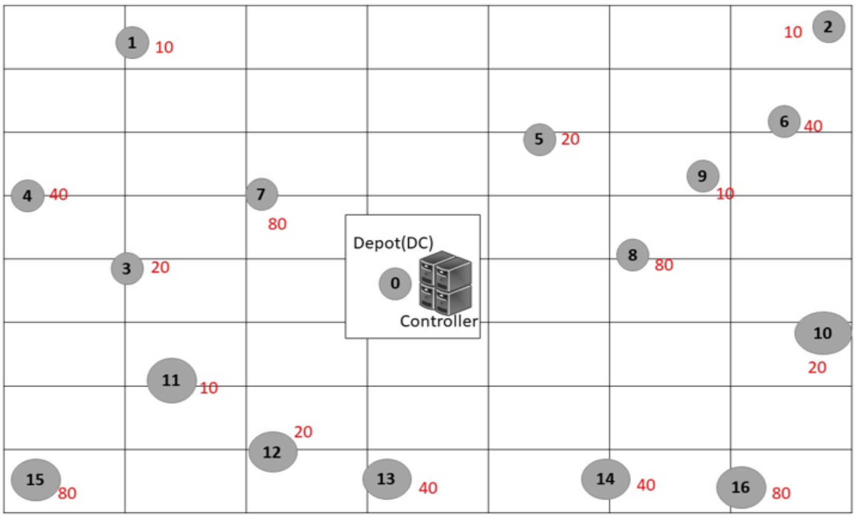

Figure 5.15: Bus Stops with Demands

Bus Stop	Demands from destination stop (TB)	Distance from Depot(0) (Km)	Bus Capacity (TB)
1	10	5.48	150
2	10	7.76	150
3	20	6.95	150
4	40	5.82	150
5	20	2.74	150
6	40	5.02	150
7	80	1.94	150
8	80	3.08	150
9	10	1.94	150
10	20	5.36	150
11	10	5.02	150
12	20	3.88	150
13	40	3.54	150
14	40	4.68	150
15	80	7.76	150
16	80	6.62	150

Table 5.3: Demands form all bus stops for data allocation

tested our objective function and observed an optimal solution while minimizing energy consumption. We have calculated energy consumed while sending data from the central depot towards the destination bus stop using our energy model characterized in Section 5.3 including uploading/downloading and transit energy. We are assuming that buses are available to carry data towards each bus stop. However, we will be calculating the energy consumption while sending data through a traditional network to show a comparison that PTDD is an energy-efficient solution for delay-tolerant data applications.

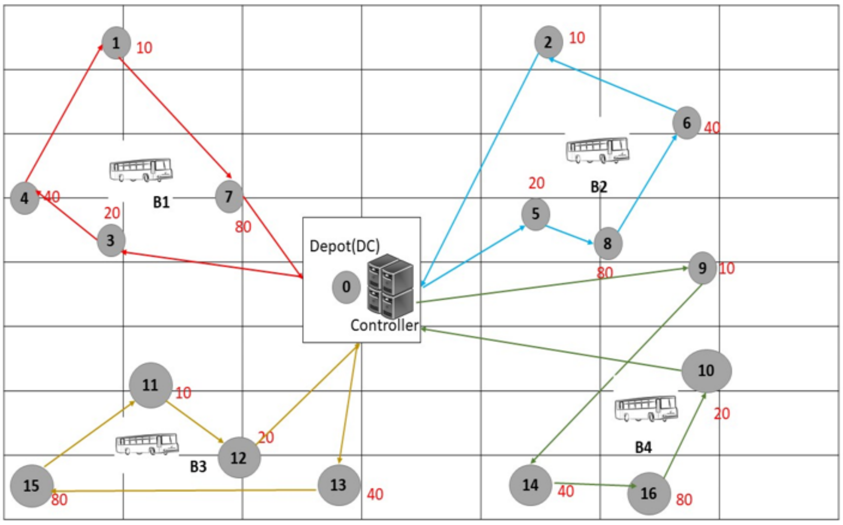

Figure 5.16: Data Allocation onto Each Bus Stop Through Buses

As per the parameters defined, we have allocated data onto four buses and they are fulfilling all requirements while minimizing energy consumption and returning to the source bus stop or depot after finishing its trip. We have defined all the bus routes with the optimal selected route for data allocation in Fig. 5.16. All the buses have a maximum 150TB capacity to carry data and allocating data to all bus stops. Table 5.4 shows the computation results of all the buses traversing all the bus stops in unidirectional format and the total distance covered during each trip.

Bus Number	**Selected route**	**Total Distance covered during the trip**
B1	0-3-4-1-7-0	12km
B2	0-5-8-6-2-0	13km
B3	0-13-15-11-12-0	12km
B4	0-9-14-16-10-0	13km

Table 5.4: Set of test trips with the number of bus stops

In our analysis, we have used 16 stops which will be covered by four buses to fulfill their demands being allocated from DC to deliver data. In Fig. 5.17, it is

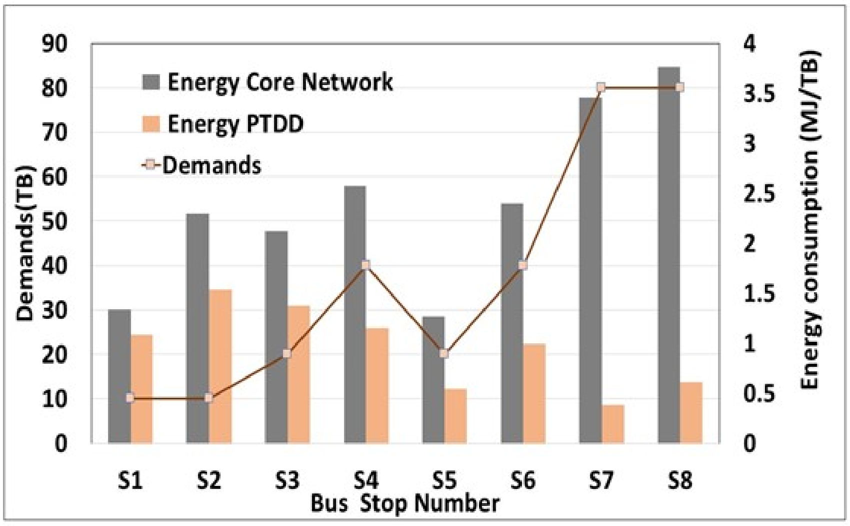

Figure 5.17: Energy Consumption Vs Bus Stop Number for Generated Demands

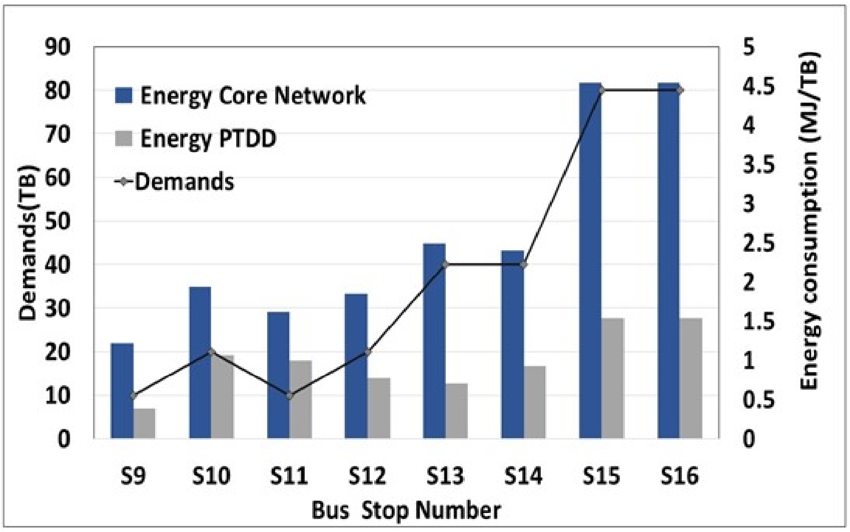

Figure 5.18: Energy Consumption Vs Bus Stop Number for Generated Demands

possible to disseminate data either from the core traditional network and PTDD in the heterogeneous network. However, if we have delay tolerant data and we can utilize public transport, PTDD is an energy-efficient solution. Bus stop 1 and 2 have demanded 10TB, Bus stop 3 and 5 has demands of 20TB, bus stop 4 and 6 ahs demands of 40TB, and bus stop 7 and 8 have demands of 80 TB.

As shown in Fig. 5.18, bus stop number 9 and 11 demands 10TB data, bus stop 10 and 12 demands 20 TB data, bus stop 13 and 14 demands for 40TB data, and bus stop 15 and 16 demands for 80TB data. The bus will carry and deliver data at each bus stop as per their demands. For the maximum demands of 80TB, we can analyze that the core network consumes 33% more energy than PTDD for data transmission.

5.7 Summary

In this chapter, we proposed a Software-defined Connectivity layer for the dynamic allocation of connections among all nodes as per their requirements for energy efficiency. The SDC controller makes forwarding decisions and gives connectivity options as per the profiles of users. We dedicated our work to a data dissemination technique in all three layers (wired network, wireless network, and Scheduled Vehicle Network). This work aims to utilize the moving ability of public transport to reduce energy consumption. Many researchers have already discussed the vehicular network to use as a data carrier, but our work combined all of the networks to use and switch according to the requirements in terms of saving energy. This strategy can be used in the case of rural areas where the wired and wireless network is not possible. For delay tolerant data needs, our approach aims to best utilize the existing public buses, hence lowering the energy consumption as per the data volume and distance during the data transmission processes. Our multi-commodity flow optimization technique performed during this work helps in network selection while proving that there is significant energy saving with the public transport network. The case study presented using CVRP helped to minimize energy consumption with a fixed capacity of buses to allocate data onto each bus stop. This work provides strong evidence that significant energy savings can be achieved while still guaranteeing data delivery.

Chapter 6

Conclusion

The main objective of this thesis is to design a sustainable data dissemination architecture using public transport networks in heterogeneous networks. We introduced public transport assisted data dissemination system as shown in Chapter 3. To support our research, we have provided an in-depth understanding of the potential to use the public transport network as an alternative communication channel.

6.1 Summary of Contributions

In this thesis, we analysed the various perspectives of traditional networks and every network have their standpoint and mode of communication. These networks mostly rely on big data analytics in the design of data communication networks. “Big Data” has become the most attractive topic nowadays in both the academic and corporate worlds. Data has been generated from many sources such as scientific research (physics, astronomy, computational biology), Internet of Things (IoT), agricultural sensors, healthcare applications, social networking websites (LinkedIn, Twitter, Facebook. etc). Therefore, these big data applications’ survivals would not be possible without the underlying support of networking due to their extremely large volume and computing complexity. Nonetheless, these data-hungry applications ultimately consume massive energy. Therefore, this biggest challenge encourages the search for more connectivity options. Many routing and forwarding techniques have been used to alleviate network congestion and make communications more energy efficient.

A literature briefing in Chapter 2 about the work done focuses on energy and network congestion reductions with good delivery probabilities. We have identified the research gap between green networking, delay-tolerant network, and heterogeneous network for more energy-efficient and sustainable solutions to be incorporated into future network architectures. We may also find many data offloading strategies in the literature to offload data onto other networks to alleviate the pressure. To achieve our research objective, we have followed the Design Science Research Methodology (DSRM). This methodology has been illustrated in different phases such as the design of the study, identify the problem, objective of the solution, design and development, evaluation and implementation, and communication. All these phases are in an iterative process to improve our research for better results. Next, we have presented an alternative communication channel named Public Transport assisted data delivery (PTDD) for sustainable data dissemination via introducing a third layer of the public transport network to the conventional wired and wireless networks. For delay tolerant data needs, our approach aims to best utilize the existing public transport, hence lower the energy consumption, and carbon footprint generated during the data transmission processes. Many researchers have already discussed the concept of vehicular networks used as data carriers, but our work combines all of the networks, such as wired, wireless, and public transport, to use and switch according to the requirements of different services. Thus, to introduce buses as an alternative communication channel, in Chapter 3, we have done the following hypothesis:

1) The road network is a fixed existing infrastructure. Buses are scheduled for a route and move all along the city as per their timetable. The mobility patterns of

buses are predictable as it travels on a fixed schedule back and forth between two bus stops. Public Transport network has a huge capacity to carry data from the source until destination with delay-tolerant features. 2) Buses are equipped with an On-Board unit and wireless interface for communication. All the bus stops are deployed with Roadside units. Data will be offloaded/uploaded onto buses from any bus stop on the bus route.

We have used the Auckland Transport dataset to analyse the capacity of the transport network. The Static aggregated graph (SAG) aggregates all the information from the bus network, timetable, pair of vertices, the overall distribution of contact occurrence over a 24-hour time window and helps to analyse the capacity of the network. In addition to it, our system framework supports delay-tolerant applications, some of the applications are delay sensitive such as online gaming, Netflix, and cannot be delayed. Therefore, we have analysed the impact of the Delay-Tolerant Indicator (DTI) on the capacity of the transport network. The finding of this chapter suggests that there is great potential in using the public transport network as an alternative communication channel.

We also applied a machine learning technique to predict the arrival time of the bus at each bus stop for data allocation. Neural Network is one of the popular models in terms of robustness and accuracy. Therefore, we have pre-processed the dataset with different functions and enhanced the Neural Network with different parameters to predict the arrival time of buses to have realistic information on bus arrival. Our ANN model proved that there is a small variation in the actual and predicted arrival time of the bus, which is acceptable for delay-tolerant applications. Further, the finding suggests there is a delay in bus arrival at some stops, but it is acceptable for delay-tolerant applications.

One of the important aspects of a heterogeneous environment is to decide the optimal network for different services. We proposed a Software-defined Connectivity architecture for network selection and data allocation in a heterogeneous network in Chapter 4 . The performance of our architecture was evaluated in two stages. First is the network selection among different networks and next is when public transport gets selected, data gets allocated onto these buses. The SDC controller makes forwarding decisions and gives connectivity options as per the profiles of users and different services. For delay tolerant data needs, our approach aims to best utilize the existing smart public vehicles and their parking spots with local storage to offload and upload data. Our scheme utilizes vehicles' patterned movement, and it matches the profile of users from a flow table to make network selection decisions for message forwarding. Accordingly, a public vehicle going in a suitable direction can carry data along with it and there is no extra fuel consumption while transmission. The SDC controller used the MADM technique for network selection among different networks based upon different attributes and criteria. The utility functions have been defined for different attributes for the user's satisfaction and the AHP method was used for network ranking. To achieve an optimal network, the AHP method evaluates subjective weight and ranks the network according to the priority. We used MATLAB to calculate weight and consistency check first and then ranking preference of network for different services. The finding of this chapter recommends that the optimal network can be selected based on different attributes and criteria.

Moving further, the SDC controller allocated data onto buses after selecting the public transport network. For data allocation, it is important to know the bus contact duration with deployed RSU and throughput at each bus stop. In the previous chapter, we predicted the arrival time of the bus, so we already know when will the bus be reaching at each stop. There is a different stay time for each bus at bus stops. The parent stops are the stops near-source and destination, and buses stay longer at parents stop. However, buses stay for a shorter duration at some stops during their trip and few of the stops are passing stops if there is no passenger, buses do not stop there. Therefore, the bus's contact duration depends on the type of bus stop, and the data gets allocated accordingly. We validated our model and calculated offloading efficiency for stopping stops and passing stops. For each passing stop, we achieved up to 60GB of offloading capacity and 160GB for stopping stop. This capacity can be increased by employing new standards of IEEE802.11ac-based WLAN and respective data rates.

Next, we have already defined our software-defined architecture in the previous chapter. However, for energy-efficient data dissemination, we defined energy consumption and delay model in Chapter 5. We have formulated our problem by using a multi-commodity min-consumption flow problem to minimize energy consumption to disseminate data from one place to another either through a traditional network or public transport network. For delay-tolerant data needs, our approach aims to best utilize the existing public buses, hence lowering the energy consumption as per the data volume and distance during the data transmission processes. We used a multi-commodity minimum-cost flow approach to analyze the best optimum solution as per the demands to fulfill the user's objectives. Next, we applied CVRP for energy-efficient data dissemination by selected buses. We evaluated our results using the SAS optimization tool while sending data using both networks while minimizing energy cost. The case study presented in this work provides strong evidence that significant energy savings can be achieved while still guaranteeing data delivery.

6.2 Future Work

This thesis provides public transport assisted data dissemination in the heterogeneous network. The traditional way is to use a core network for data dissemination, we are using existing road infrastructure as an alternative communication channel to disseminate data from one place to another. Our research objective is to design a sustainable data dissemination architecture in a heterogeneous network. To aim our objective, we have represented our system model with the Auckland transport case study in all our contributions. This work anticipates the development of the future area to be further explored.

- **Extension of PTDD**

  In this thesis, we have designed public transport assisted data dissemination system as an alternative communication in Chapter 3. However, the proposed method could be affected by the high dynamic changes in network topologies. Therefore, in addition to the existing transport network with a static dataset, the network should be developed with dynamic factors such as traffic, weather, passenger flow data, etc for real-time changes in the network. An analytical model for dynamic behaviors of bus movement shortly can be a good contribution.

- **Incentive mechanism for participation**

  To promote this strategy as the best solution for data dissemination with delays, incentive mechanisms can be introduced as part of our future work. The moving crowd can be incentivized with either monetary or non-monetary rewards to use a scheduled vehicle as a data dissemination medium as they are already placed (and running) and to utilize them for energy- efficiency. Many incentive mechanisms have been introduced in the literature for offloading and using the alternative network for traffic alleviation. The monetary Incentives are a direct benefit to users and users can easily judge that it satisfies their expectations or not and finally can take a decision. Some non-monetary Incentives includes barter, reputation, social, and gamification based incentives for the users to promote. Some social-based strategies include their social relationship and social network (Facebook, Twitter) and users cooperate even with strangers to expect cooperation in the future. Therefore, this incentive mechanism can be introduced in the future to promote PTDD.

- **Applying Cognitive Connectivity**

This thesis adopted a Multi-attribute decision-making strategy for network selection. We defined utility functions and weighing methods like AHP for network ranking. In addition to these parameters, cognitive radio mechanism can be applied in future at physical layer public transport be selected as a communication medium dynamically.

- **Trust and Security**

  In the proposed thesis, we are using public transport for data dissemination. However, the privacy and security part is lacking in our proposed work and will be considered as future work and an extension of our proposed architecture. Not only this, more challenges can be taken into account while developing a trust-based framework such as secure data dissemination. Trust and security will enhance the performance of our proposed system and will motivate users to use public transport as an alternative communication channel.

- **Data accumulation process**

  The data gets accumulated at the nearby bus stop in our processed framework. We have used the Machine Learning(ML) technique for bus arrival time prediction to have their realistic information to allocate data onto them. We can further use the ML technique for data accumulation to improve the reliability of communication. All smart cities are equipped with smart sensors for smart monitoring. These ML techniques can help to process huge data, to detect patterns and features that remain unnoticed using outdated approaches. In addition to this, the data accumulation process has great potential in other research areas for data analysis and mining for the next level approach.

6.3 System Implications

We have proposed PTDD system for data dissemination. The main motive is to use PTDD as an alternative communication channel in the heterogeneous network for energy saving. To achieve our research objective, we have conducted an experimental analysis using the Auckland transport case study in all contributions to prove that PTDD can be energy-efficient data dissemination architecture. There is a various area that our work can be further applied.

Any unexpected disaster either naturally occurred or caused by human actions firstly results in damage to the communication medium. Although many of the technologies have been introduced for disaster management and try best to connect the affected area with the rest of the world. However, in the post-disaster scenario, compared to the building and any BS, vehicles can be quickly moved to the affected area. In particular, public transport is firstly available to fulfill people's basic needs. Therefore, our PTDD can be efficiently utilized as a mobile communication backbone in disaster management. Public transport is an existing infrastructure, we do not need any infrastructural changes in such circumstances.

The main objective of our research is to use the existing public transport network for data dissemination. Whenever a user wants to send big data from one location to another, the user's profile is being monitored by the central controller, who take forwarding decision based upon his profile and flow table. The central controller identifies nearby bus stop for data offloading and then find suitable going onto that direction based upon the schedule or timetable of that bus on that route. Therefore, these buses are utilized efficiently for data migration. There are many existing solutions for data migration such as Amazon's service snowball, iCloud, etc. But our solution outperforms in terms of energy-efficiency and less expensive and ultimately releases the congestion from the core network.

Another important implication of our work is the video surveillance system. The transport agency has deployed people with the camera to notice people going into T3/T2 lanes. The public transport belongs to the same transport agency, If these cameras get deployed onto bus stops and these buses can be utilized for carrying that accumulated data to the main center. These videos are not urgent and can be delayed up to hours for delivery. Not only that, many smart cities have mounted cameras all around the city to minimize the crime rate. This camera's storage capacity is in PB and consumes a lot of network bandwidth to access this data and results in network congestion and poor quality. This footage is important but not urgent and PTDD can be utilized efficiently to alleviate this network congestion.

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Appendix A

Glossary

3G Third-Generation

4G Fourth-Generation

5G Fifth-Generation

AHP Analytical Heirarichal Process

ANN Artificial Neural Network

AODV Ad hoc On-Demand Distance Vector

AP Access Points

AT Auckland Transport

BS Base Stations

BWA Broadband Wireless Access

CO2 Carbon Emission

CPS Cyber-Physical Systems

CPU Central Processing Unit

CR Consistency Ratio

CR Communication Range

CSV Comma-Separated Values

DC Data Centre

DSR Dynamic Source Routing

DSRM Design Science Research Methodology

DTI Delay-Tolerant Indicator

DTN Delay Tolerant Network

EC Energy Cost

EE Energy Efficiency

FTTH Fiber To The Home

GPS Global Positioning System

GTFS General Transit Feed Specification

I2I Infrastructure-to-Infrastructure

ICT Information and Communications Technologies

IP Internet Protocol

ISPs Internet Service Provider

LTE Long Term Evolution

MADM Multi-Attribute Decision Making

MANET Mobile Adhoc Network

MAPE Mean Absolute Percentage Error

MULE Mobile Ubiquitous LAN Extensions

NN Neural Network

NZTA NZ Transport Agency

OBU Onboard Units

ONE Opportunistic Network Environment

OPEX Operational Expense

OSI Open System Interconnection reference model

PLE Path Loss Component

PTDD Public Transport Assisted Data Dissemination System

QoS Quality Of Service

RI Random Index

RIP Routing Information Protocol

RSU Rad-side Unit

RSUC Roadside Unit Centers

SAG Static Aggregated Graph

SDC Software-Defined Connectivity

SDN Software-Defined Network

SMAPE Symmetric Mean Absolute Error

SNR Signal to Noise Ratio

SQL Sequential Query Language

TT Travel Time

TTL Time-To-Live

UMTS Universal Mobile Telecommunications System

V2I Vehicle to Infrastructure

VANET Vehicular Ad hoc Networks

VDSL Very High-Speed Digital Subscriber Line

VDTN Vehicular Delay-Tolerant Network

VNI Visual Networking Index

WLAN Wireless LAN