# Vehicle-to-Vehicle Forwarding in Green Vehicular

Infrastructure

## VEHICLE-TO-VEHICLE FORWARDING IN GREEN VEHICULAR INFRASTRUCTURE

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To my family whom stayed while everyone else left.

## Abstract

Smart scheduling can be used to reduce infrastructure-to-vehicle energy costs in delay tolerant vehicular networks (Hammad et al., 2010). In this thesis we show that by combining this with vehicle-to-vehicle (V2V) forwarding, energy efficiency can be increased beyond that possible in the single hop case. This is accomplished by having the roadside infrastructure forward packets through vehicles which are in energy favourable locations. We first derive offline bounds on the downlink energy usage for a given input sample function when V2V forwarding is used. Separate bounds are given for the off-channel and in-channel forwarding cases. These bounds are used for comparisons with a variety of proposed online scheduling algorithms. The paper then introduces online algorithms for both fixed bit rate and variable bit rate air interface options. The first algorithm is based on a greedy local optimization (GLOA). A version of this algorithm which uses a minimum cost flow graph scheduler is also introduced. A more sophisticated algorithm is then proposed which is based on a finite window group optimization (FWGO). Versions of these algorithms are also proposed which use in-channel vehicle-to-vehicle scheduling. The proposed algorithms are also adapted to the variable bit rate air interface case. Results from a variety of experiments show that the proposed scheduling algorithms can significantly improve the downlink energy requirements of the roadside unit compared to the case where vehicle-to-vehicle packet forwarding is not used. The performance improvements are especially strong under heavy loading conditions and when the variation in vehicle communication requirements or vehicle speed is high.

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# Notation and abbreviations

$\mathbf{AP}$	Access Point
CBR	Constant Bit Rate
CCH	Control Channel
$\mathrm{DL}$	Down-Link
DNFG	Dynamic Network Flow Graph
$\mathbf{EE}$	Energy Efficiency
ERA	Earliest-RSU-Arrival
FIFO	First Come First Serve
FWGO	Finite Window Group Optimization
GLOA	Greedy Local Optimization Algorithm
IC	In-Channel
ICT	Information and Communication Technology
ILP	Integer Linear Program
ITS	Intelligent Transportation System
MAC	Medium Access Control
MANETs	Mobile Ad-Hoc Networks
MCFG	Minimum Cost Flow Graph

MILP	Mixed Integer Linear Program
NFS	Nearest Fastest Set
$\mathbf{QoS}$	Quality of Service
PHY	Physical
$\mathbf{RSU}$	Road Side Unit
SCH	Service Channel
TDMA	Time Devision Multiple Access
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VANETs	Vehicular Ad-Hoc Networks
VBR	Variable Bit Rate
VII	Vehicle Infrastructure Integration
WAVE	Wireless Access in Vehicular Environment
WLAN	Wireless Local Access Network
WMN	Wireless Mesh Network

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## Chapter 1

## Introduction

In the future, Vehicular Ad-Hoc Networks (VANETs) will enable a wide variety of applications ranging from road safety, to those including context-aware advertising and Internet media streaming. VANETs are currently being designed based on spectral licensing in the 5.9 GHz frequency band (Federal Communications Commission, 2004) and via vehicular specific standards such as Wireless Access in Vehicular Environment (WAVE), which is derived from the IEEE 802.11 wireless LAN standard (Uzcategui and Acosta-Marum, 2009). Aside from the obvious commercial interests in VANETs, they have also drawn a lot of recent attention from researchers, due to their unique technical issues (Hartenstein and Laberteauz, 2008). This area is the focus of this thesis.

### **1.1 Energy Efficiency in Communication Systems**

The 21st century is facing serious energy related problems, such as energy availability, pricing and its environmental impact. Reference (Chong *et al.*, 2011) has stated: "In 2007, the whole information and communications technology (ICT) industry accounted for about 3 percent of the worldwide energy consumption and contributed about 2 percent of the CO2 emissions. It is expected that the growth of the ICT footprint will be less than double between 2007 and 2020, whereas that of mobile communications will nearly triple in the same period."<sup>1</sup> For this reason, efficient and environmental friendly use of energy is considered a necessity for future telecommunication systems. However, it is well known that current implementations, especially those which use fixed power grid connections, have rarely been designed to be energy efficient. This shortcoming has resulted in the advent of "Green Radio Communication Networks" which is attracting attention from many researchers (Chong *et al.*, 2011). For example, it was not until recently that energy efficiency in cellular base stations gained importance (McLaughlin *et al.*, 2011). In the past, the focus has mainly been on system performance measures such as throughput rather than on energy efficiency (Chen *et al.*, 2011). Future work needs to more fully consider the tradeoffs between these two objectives. This is also true for vehicular ad-hoc networks.

### 1.2 Energy Efficiency in VANETs

Energy efficiency in vehicular ad-hoc networks has typically not been considered an issue. This stems from the fact that a significant part of the literature focuses solely on vehicle-to-vehicle communication. In this mode of operation, energy is assumed to be unlimited since communications is powered by the vehicle engine. In addition, roadside infrastructure often assumes settings where wired power is readily available. However, this is not always the case, and a serious barrier to significant roadside

<sup>&</sup>lt;sup>1</sup>Chong et al., IEEE Wireless Communication, October 2011

infrastructure deployment is the cost of providing electrical power to the deployed nodes.

A viable alternative to power grid connections, is to operate roadside infrastructure using green energy sources, such as solar or wind power. In (Peirce and Mauri, 2007) a study was presented by the US Department of Transportation's Vehicle Infrastructure Integration (VII) Initiative. This report includes cost estimates for a significant vehicular infrastructure build-out that would initially focus on vehicle monitoring and safety. It was estimated that about 40% of all rural free-way roadside infrastructure would have to be solar powered, and that roughly 63% of the roadside unit costs would be associated with solar energy provisioning, i.e., mainly panel and battery costs. The total cost estimates comes to just under 1B dollars for the initial deployment round. Clearly, these costs can be reduced by energy efficient roadside infrastructure designs. In vehicular infrastructure, proper traffic scheduling can lead to significant improvements in energy efficiency due to the strong dependence of power consumption on RSU-to-vehicle distance (Hammad *et al.*, 2010).

### **1.3** Smart Vehicular Scheduling

Unlike many traditional wireless networks, vehicles may only remain within roadside infrastructure radio coverage for relatively short periods of time. This property raises the question of how vehicles should be served when passing through roadside coverage areas. Extensive research has already considered this problem and various schedulers have been proposed as will be discussed in Section 2.6.

In certain vehicular scenarios, the location of vehicles passing through the RSU radio coverage area can be predicted with a high degree of accuracy. This information



Figure 1.1: Roadside Unit (RSU) Example. Vehicles v and w are served by a single RSU as they pass through its coverage area at time t. Communications with Vehicle w at time t is preferable if  $d_v \gg d_w$ , since v and w are moving towards, and away from, the RSU, respectively.

can then be used to reduce downlink infrastructure-to-vehicle energy costs provided that there is sufficient packet delay tolerance (Hammad *et al.*, 2010). An example of this type of scenario is shown in Figure 1.1 at some time t, when the RSU can communicate with either Vehicle v or w. In the example given,  $d_v \gg d_w$ , so from an energy viewpoint the RSU would prefer to communicate with Vehicle w. Clearly this will be advantageous if at some time later, Vehicle v is in a more energy favorable location. This illustration shows that it is possible to reduce overall energy use by smart scheduling.

### 1.4 Thesis Overview

In this thesis we show that by combining smart vehicular scheduling with vehicleto-vehicle packet forwarding, infrastructure energy efficiency can be significantly increased beyond that described in (Hammad *et al.*, 2010). Since vehicles have virtually unlimited energy reserves, vehicular forwarding does not incur infrastructure energy

costs. Roadside infrastructure can therefore reduce energy usage by forwarding packets through vehicles which are in energy favorable locations. We first derive offline bounds for the downlink energy required for a given input sample function when vehicular forwarding is enabled. Bounds are given for both the off-channel and in-channel forwarding cases. A formulation based on dynamic network flow graphs is developed for the in-channel forwarding case. The offline bounds are used for comparisons with proposed online scheduling algorithms. Then we introduce online algorithms for both fixed bit rate and variable bit rate air interface cases. The first algorithm uses a greedy local optimization (GLOA). A version of the algorithm is also given which uses a more sophisticated minimum cost flow graph scheduler. An algorithm is then proposed which is based on a finite window group optimization (FWGO) where vehicle groups are formed and scheduled jointly. Versions of these algorithms are also proposed which use in-channel vehicle-to-vehicle scheduling, and the proposed algorithms are adapted to the variable bit rate air interface case. Results from a variety of experiments show that the proposed scheduling algorithms can significantly improve the downlink energy requirements of the roadside unit compared to the case where vehicle-to-vehicle packet forwarding is not used. The performance improvements are especially strong under heavy loading conditions and when the variation in vehicle communication requirements or vehicle speed is high.

The remainder of the thesis is organized as follows. In Chapter 2 an overview is given of related work. In Chapter 3, first we give a detailed description of our system assumptions in Section 3.1. Then in Section 3.2 we formulate lower bounds on the energy needed to satisfy downlink vehicular communication requirements. Both constant bit rate (CBR) and variable bit rate (VBR) air interface assumptions are considered. Chapter 4 then presents a variety of online scheduling algorithms for both the CBR and VBR cases. These algorithms include those based on schedulers derived using minimum cost flow graph (MCFG) and dynamic network flow graph (DNFG) constructions. Performance results are then presented in Chapter 5 which show that under certain conditions, significant reductions in roadside infrastructure energy use can be obtained using the proposed schedulers. Finally, the conclusions of the thesis are presented in Chapter 6.

## Chapter 2

# A Brief Review of Vehicular Ad-Hoc Networks (VANETs)

Research in vehicular networks has spanned a wide variety of topics in recent years. This includes areas such as applications (Khaled *et al.*, 2009), routing algorithms (Li and Wang, 2007), authentication (Zhang *et al.*, 2009), scheduling (e.g., (Hammad *et al.*, 2010; Zhang *et al.*, 2007; Alcaraz *et al.*, 2009)), and the performance analysis of the IEEE 802.11p standard (Mittag *et al.*, 2008). In this chapter we give an overview of this activity.

## 2.1 VANET Applications

VANETs applications can be divided into two major categories, safety and user applications. The vision for VANETs design were that safety applications would be supported initially, and this would be followed by fixed infrastructure supported user applications.

### 2.1.1 Safety Applications

According to (Toor *et al.*, 2008), 60% of road accidents could be avoided if half a second beforehand, the driver would have been provided with some kind of warning. Communication via vehicular networking can help to enable these types of warnings. Vehicle safety related applications usually require reliable and fast message delivery which is one of the major VANETs challenges today (Ma *et al.*, 2012). Some examples of VANETs safety related applications are as follows.

- When an accident occurs, especially where vehicles are traveling at high speed, they often crash before they come to a complete stop. Safety applications can be developed which provide warnings when an accident occurs, giving approaching vehicles enough time to react to the incident. Also, with the use of position awareness, a safety application can be used to provide drivers with early warnings or signs to prevent accidents in the first place.
- At hidden intersections, applications can provide drivers with the position of other vehicles and provide warnings when collisions are more likely.
- A capability discussed in (Khaled *et al.*, 2009) is incident management. The aim of such an application is to manage an existing accident, which can be done by obtaining location and extent information, which can be used to direct traffic flow.
- Information about current traffic conditions, parking availability, etc., can be provided. This, in addition to estimated positions of other vehicles, can be used to provide drivers with the best route to their destinations, thus preventing traffic congestion (Toor *et al.*, 2008). Also, road signaling control is available

and it is possible to develop algorithms such as the one proposed in (Nafi and Khan, 2012). Other services can be provided along the same lines such as vehicle tracking and notification (Khaled *et al.*, 2009).

### 2.1.2 User Applications

User applications span a wide range of possibilities, e.g., Internet access through road side infrastructure, multimedia streaming and advertisements. These can be categorized as follows.

- Internet Access through road side infrastructure, which opens up a wide range of application and economic opportunities.
- Peer-to-Peer applications, such as multi-player games and media sharing between vehicle passengers.

To successfully support these types of applications, an underlying reliable communication platform is critical. Current application design paradigms can be divided into two basic categories: Those which require only vehicle-to-vehicle communication and those which need the support of fixed infrastructure (Khaled *et al.*, 2009).

### 2.2 Routing Algorithms

VANETs are dynamically formed networks which make message routing a challenging task. The network topology may be rapidly changing, and routing decisions must take this into account. Also, the random nature of vehicle speeds and direction should be considered. Routing protocols can be divided into five categories (Li and Wang, 2007).

- Ad-Hoc routing: Since VANETs and MANETs (Mobile Ad-Hoc Networks) share many of the same design principles, many ad-hoc routing algorithms are applicable to VANETs, such as AODV (Ad-Hoc on Demand Distance Vector) (Perkins and Rover, 1999) and DSR (Dynamic Source Routing) (Johnson and Maltz, 1996). AODV and DSR are designed for general ad-hoc networks, however VANETs differ in some respects, especially due to their highly dynamic topology. Comparisons of these routing protocols under various traffic conditions has been the subject of several studies. These have shown that many existing ad-hoc routing protocols perform poorly, because they tend to have slow route convergence and a resulting low throughput (Li and Wang, 2007). Reference (Wang et al., 2005) shows that AODV is unable to find, keep and update long routes, and therefore, adjustments must be made. For example, in order to reduce the effect of link breakage, several prediction-based AODV protocols have been proposed, i.e., PRAODV and PRAODVM (Li and Wang, 2007). These use speed and positional information to predict route lifetime. PRAODV constructs a new route before the end of a route's predicted lifetime and PRAODVM selects the maximum lifetime path from among several routes instead of using shortest paths, as in AODV and PRAODV (Li and Wang, 2007).
- Position-based routing: Although VANETs topologies are highly dynamic, the movement of vehicles is restricted to roadways. Accordingly, routing strategies have been proposed that are based on geographical map location information. A number of studies, e.g., (Liu *et al.*, 2004; Fler *et al.*, 2003), showed that geographical based routing protocols are more promising than topology based

options such as AODV and DSR. Although position information can be useful to vehicular nodes, position-based routing protocols still have challenges to overcome. GPRS (Greedy Perimeter Stateless Routing) is one of the best known position-based routing protocols (Karp and Kung, 2000), which uses a combination of face routing and greedy routing. Face routing is used to move out of local minima when greedy routing fails (Li and Wang, 2007). Several studies, e.g., (Liu *et al.*, 2004; Fler *et al.*, 2003; Lochert *et al.*, 2003), have considered the effect of GPRS under city and highway conditions, and the problems with GPRS have been identified. First, since direct communication links are not always available in city settings, greedy forwarding is often restricted. Second, mobility can cause problems for face routing. Finally, forwarding packets in the wrong direction may occur, which creates increased packet latency and overhead.

- Cluster-based routing: In order to provide scalability, a virtual network is created by node clustering. Each cluster will have a cluster-head that will take care of all inter- and intra-cluster coordination. Several studies, e.g., (Lin and Gerla, 2002; Bharghavan and Das, 1997), have proposed multiple cluster based routing schemes in MANETs. However, VANETs behave differently due to vehicular speed, driver behavior, and constraints on mobility. For these reasons, existing MANET clustering techniques tend to be unstable in VANETs (Li and Wang, 2007). However, several improved clustering techniques have been suggested for VANET applications (Blum *et al.*, 2003).
- Broadcast routing: Some VANET applications, such as traffic sharing, emergency notification, weather reporting and road condition alerting frequently use

this method (Li and Wang, 2007). A simple way to implement a broadcast is for every vehicle to send the message to all of its neighbors with the exception of the vehicle from which it received the message. This is referred to as flooding. More complex protocols for broadcasting have also been proposed. For example, Durresi *et al.* proposed an emergency broadcast protocol, BROADCOMM, for highway network settings. Urban Multi-Hop Broadcast protocol (UMB) presented in (Korkmaz *et al.*, 2004) is another example of broadcast routing. It is designed to defeat hidden terminal, interference and packet collision problems.

• Geocast routing is a location based multicast routing protocol. The goal is to deliver packets from one particular node to all other nodes in a specific geographical location. Some VANET applications can benefit directly from geocast routing. For example, when a vehicle encounters an emergency, it can report the incident to nearby vehicles. Geocast routing can be easily implemented with a multicast routing protocol by defining the group to be vehicles in a particular geographical area (Li and Wang, 2007). In (Maihofer, 2004) a survey of geocast routing can be found.

### 2.3 Security and Authentication

Some commercial and safety applications in VANETs require a high level of security. This motivates the need for data authentication. A survey of security attacks in VANETs has been discussed in (Alkahtani, 2012).

To implement authentication, messages typically use a public key signature. To ensure that the public key belongs to a certain node, a public key infrastructure is necessary. In the current IEEE 1609.2 proposal, data authentication is done using an algorithm called the Elliptic Curve Digital Signature. However, there are some drawbacks with this algorithm. First, the hardware cost for implementing such a complex algorithm tends to increase with the number of incoming messages. In a typical vehicular network, a vehicle may receive up to 2500 messages per second. Therefore providing capable hardware may substantially affect the cost. Second, vehicle transceivers are usually small and cannot support such complex mathematical computations (Hartenstein and Laberteauz, 2008). Accordingly, message authentication is still an active research area in VANETs, and new protocols are currently being developed. An interesting protocol suggested in (Zhang et al., 2009) uses a decentralized group-authentication method. Instead of a central authority, each RSU maintains its own group. The paper proposes to have each RSU keep and manage an on-the-fly group within its communication range. Vehicles in the group can communicate with other vehicles, i.e., vehicle-to-vehicle messaging, which can be authenticated instantly. If a message turns out to be invalid, a third party can expose the identity of the source. One important aspect of the proposed scheme is that the resulting network will be scalable.

### 2.4 Medium Access Control (MAC) Protocols

Medium Access Control is one of the key designs in wireless communication systems. Two major classifications for MAC protocols are:

• Contention based, which are often based on carrier sensing, back-off and retry protocols, and,

• Contention free, which normally relies on dynamic time division multiple access (TDMA).

The method to coordinate medium access can range from completely random access, where any of the nodes asynchronously access the medium with very little coordination, to a more centralized approach, where specific time slots are allocated to particular nodes. Contention based methods tend to be more robust since there is very little central coordination required. On the other hand, performance can deteriorate significantly with increased traffic load due to contention overhead. In the contention free methods, a higher level of coordination is required, which is not always easy in VANETs. Generally, Quality of Service (QoS) constraints are easier to guarantee in the contention free protocols (Booysen *et al.*, 2011). Among existing MAC protocols for VANETs, most have focused on vehicle to infrastructure communication rather than the vehicle to vehicle case (Booysen *et al.*, 2011).

### 2.4.1 MAC Design for VANETs

MAC solutions derived from existing wireless standards tend to be less reliable when applied to VANETs, due to the effects of high node mobility. In (Kenny, 2010), a discussion of different objectives and some of the technical problems in MAC design have been discussed, and are summarized as follows.

• The hidden terminal problem arises when two vehicles are outside communication range but wish to communicate with a vehicle that is within range of both. This problem is more likely to happen in networks where no infrastructure is in use.

- Based on the dynamic nature of VANETs, e.g., position, speed and direction, the wireless channel can vary rapidly. This has been addressed in IEEE 802.11p standard by reducing bit rate levels compared with conventional IEEE 802.11 (IEEE, 2006).
- Different application requirements result in different network design requirements. An appropriate level of QoS must be guarantied for safety and critical messaging. Given that the network may also be used for non-safety purposes, the QoS of non-safety applications need not be as stringent.
- Frequent disconnection between nodes is possible because of the highly dynamic nature of the network topology. Any MAC protocol for VANETs should therefore be optimized for frequent hand-offs.

### 2.4.2 IEEE 802.11p MAC Standards

The Distributed Coordination Function (DCF) is the basic MAC technique used in IEEE 802.11 networks, which is based on the CSMA/CA contention mechanism. Senders wait for a random countdown time before they transmit, ranging from zero to a maximum value which is called the contention window (CW). If they sense transmission activity during the contention window, the countdown pauses. In CSMA/CA, all the transmisions need an ACK (acknowledgement) to confirm successful reception. If transmission was unsuccessful, the CW is doubled. Contrary to IEEE 802.11 networks, in the MAC and PHY layers of IEEE 802.11p an authentication and association does not take place. This is due to the special requirements of VANETs, e.g., timing conditions. Furthermore, the Basic Service Set (BSS) defined in the original IEEE 802.11 networks have been replaced with WAVE-BSS (WBSS). In WAVE any node can transmit as long as it obtains a WBSS announcement from a WBSS provider (Qian and Moayeri, 2009). Synchronization is accomplished by dividing the channel into 100msec intervals, where each interval consists of a Control and a Service Channel (CCH and SCH) (IEEE, 2006). Safety applications necessitate guaranteed QoS which cannot be achieved by current IEEE 802.11p standards (Booysen *et al.*, 2011)

### 2.5 Mobility Models

Accurate models for vehicular mobility and traffic flow are very important and have been the topic of study for several decades (Hartenstein and Laberteauz, 2008). These have special importance in VANETs since it is very expensive to carry out experimental work in real vehicular settings (Harri *et al.*, 2009). A survey of different mobility models and issues have been published in (Harri *et al.*, 2009; Martinez *et al.*, 2011). Some of the issues are summarized as follows.

- Realistic and accurate topology maps: Vehicular motion is restricted by roads and their associated restrictions, e.g., speed limits and directions. These must be included in realistic mobility models.
- Attraction and Repulsion points: Route sources and destinations are not completely random. For instance, in many scenarios drivers are moving towards common locations, e.g., office buildings, university campuses.
- Timing information: Traffic densities often vary throughout the day.
- Intersection management: Clearly traffic regulations, traffic lights, speed changes

near intersections will affect motion patterns.

Although realistic mobility models have to consider the above types of complex behaviors, researchers often use much more simplistic models. According to (Harri *et al.*, 2009), vehicular mobility models can be classified into four categories:

- Synthetic Models: This category includes stochastic models which include random motion. Stochastic models vary in complexity and can be as simple as Poisson process arrivals using parameters which are tuned to realistic situations (Wang, 2005; Khabazian and Ali, 2008). There are other classes of synthetic models, e.g., traffic stream models, car following models and queue-based models. Traffic stream models view vehicular motion as a hydrodynamic phenomenon. Queue models consider the roads as FIFO (First Come First Serve) queues and cars as customers. In Car Following models each vehicle behaves according to the vehicle ahead. Tuning the characteristics of these types of models with realistic parameters is important for developing a good synthetic model.
- Survey-based Models: Surveys can be an important source of macroscopic mobility information. Using survey information and statistics, one is able to develop a generic mobility model which is able to to reproduce pseudo-random or deterministic behavior for urban or highway traffic.
- Trace-based Models: The complexity of vehicular mobility results in few synthetic models that can closely simulate realistic traffic flow. Therefore, instead of developing complex models and then tuning them with mobility traces or

surveys, one can save time by directly extracting generic mobility patterns from movement traces. This is the basis behind trace-based models.

• Traffic Simulator-based Models: Using complex synthetic models based on real vehicle traces or surveys, some researchers have been successful making realistic traffic simulators. Simulators that have been designed for urban traffic engineering, such as PARMICS (Paramics), CORSIM (McTrans) and VISSIM (PTV) are able to model urban microscopic traffic. However, these simulators generally cannot be used for network simulation, as there is no interface that is mutually compatible.

### 2.6 Traffic Scheduling

In VANETs, vehicles often remain within RSU coverage areas for a short period of time. This characteristic raises the question of which order vehicles should be served and several studies have addressed this problem. Traffic scheduling at the roadside unit has been considered by Zhang *et al.* where simple schedulers are used based on data size and deadline but without considering the energy consumption of the infrastructure. In (Alcaraz *et al.*, 2009) an optimization is used to maximize the total throughput of an RSU given the locations and velocities of the vehicles in range. A scheduler was proposed which is suitable for use in the contention free period of IEEE 802.11e. Reference (Nandan *et al.*, 2005) considered the use of ad-hoc forwarding as a way of reducing the access load in an infrastructure based vehicular content delivery network. In these references, however, the energy consumption of the RSU was not taken into consideration.

Energy efficient RSU scheduling has been studied in Reference (Zou *et al.*, 2011). Given a set of RSUs, this work formulates an optimization that minimizes RSU energy consumption by switching RSUs on and off, subject to maintaining full network connectivity. However, unlike this thesis, they do not schedule vehicle-to-infrastructure communication.

Recently, Hammad *et al.* suggested schedulers in an effort to minimize energy consumption of the RSU. The experiments used a distance dependent path loss component for modeling the wireless channel, and Poisson process vehicle arrivals. A simple heuristic called NFS (nearest fastest set) was proposed which assigns time slots using an Earliest-RSU-arrival scheme, e.g., requests are scheduled when vehicles are as close as possible to the RSU. Schedulers were also proposed with given priority to vehicles with higher speed, and the performance of these schedulers were compared to optimal offline solutions (Hammad *et al.*, 2010). In (Hammad *et al.*, 2013) it was shown that the packet-based problem can be formulated as a generalization of the classical single-machine job scheduling problem with a tardiness penalty, referred to as  $\alpha$ -Earliness-Tardiness. It was proven that under a simple distance-dependent exponential radio path loss model, the scheduling problem is NP-complete. Time slot scheduling was formulated as a Mixed Integer Linear Program (MILP) that was shown to be solvable in polynomial time using minimum cost flow graphs. However, vehicle-to-vehicle communication was not considered, and is the focus of our work.

## Chapter 3

## Vehicle-to-Vehicle Forwarding

### 3.1 System Model

A single Roadside Unit (RSU) is assumed that is serving vehicles passing by in one or more directions as shown in Figure 1.1. Although the figure shows traffic moving in a single direction, the scheduling algorithms and results in this thesis are equally applicable to multi-way vehicular traffic. We consider the energy use of the radio interface that the RSU uses to communicate with the vehicles on the downlink (i.e., RSU-to- vehicle) direction. Since the vehicle radio is powered by the car's engine, we are not concerned about vehicular energy efficiency. Also, we assume that the RSUs are isolated in that all co-channel interference has been neglected. However, the energy cost estimates that are used could include interference effects, if desired.

The objective of the RSU is to minimize its energy use subject to satisfying the communication requests associated with vehicles passing through its coverage area. It is also assumed that vehicular communication may occur any time throughout a given vehicle's RSU transit time, that is, the communication is delay tolerant for the

time period when the vehicle is within RSU coverage range. When a vehicle first enters the coverage range area of the RSU, it communicates its downlink communication requirement, current position and speed to the RSU, information which may be obtained via GPS inputs for example, and which can be used to estimate the vehicle's position. The objective is to schedule incoming vehicular requests so that downlink (DL) energy use is minimized. This energy consumption may be modeled differently depending upon the type of air interface that is being used. We will consider two cases, as follows.

- 1. Constant Bit Rate (CBR): In the CBR case, power control is used to maintain a fixed bit rate over the RSU-to-vehicle links as the channel path loss changes. In this case the objective is to schedule downlink transmissions such that the required average downlink *power consumption* is minimized. In this model, channel time is assumed to be a contiguous stream of time-slots, where each time slot can carry *B* bits, regardless of vehicle position within the coverage area of the RSU. The objective of a scheduler is to satisfy incoming downlink vehicular requests with the minimum possible energy.
- 2. Variable Bit Rate (VBR): In the VBR case, the transmission power used by the RSU is assumed to be fixed, and changes in channel path loss are compensated for by varying the bit rate used over the RSU-to-vehicle links. A given packet transmission may therefore occupy a different amount of time based on the bit rate used when it is transmitted. For this reason, it is convenient to consider the time-line as a contiguous stream of frame epochs, where frame period f is of duration  $\tau_f^{-1}$ . When scheduling is performed, the scheduler must ensure

<sup>&</sup>lt;sup>1</sup>For generality we assume that frames can have different durations. In practical systems such as



Figure 3.1: Roadside Unit (RSU) Multihop Example. Instead of direct RSU-to-vehicle transmission, the RSU transmits to vehicle v via multihop forwarding through vehicle w. This may offer an energy savings advantage.

that the total duration of packet transmissions occurring in frame f must not exceed  $\tau_f$ . In this case the objective of a scheduler is to schedule downlink transmissions such that the *total time* that the RSU spends transmitting is minimized.

In both cases it is usually advantageous to serve vehicles when they are as close as possible to the RSU. This results in lower CBR transmission power requirements and correspondingly higher data rates in the VBR case. This will tend to reduce downlink power consumption or downlink transmission time, respectively. In both cases the transmit power or bit rate needed can be set in a variety of ways such as using a short two-way handshake prior to actual vehicle data packet transmission.

As discussed previously, Figure 1.1 shows the situation where all RSU communication is single-hop, using direct RSU-to-destination vehicle communications as considered in (Hammad *et al.*, 2010). In Figure 3.1 we show the case where downlink transmission may also occur via vehicular multihop forwarding. For simplicity, at first we will assume that the vehicle-to-vehicle forwarding is done using a separate radio, but bounds and online algorithms have also been considered for the in-channel IEEE 802.11, frame times of this type are typically fixed in duration. radio case. The inputs and outputs of our scheduling problem are summarized as follows.

- **INPUT:** We consider a finite sequence of V arriving vehicles indexed by the set  $\mathcal{V} = \{1, 2, \ldots, V\}$ , where each vehicle v has a given RSU-to-vehicle communication requirement,  $R_v$  bits. The entire time considered in the CBR case consists of T time slots given by the set  $\mathcal{T} = \{1, 2, \ldots, T\}$  over which the scheduling is to occur. In the VBR case the time considered is the set of frames  $\mathcal{F} = \{1, 2, \ldots, F\}$  and their duration,  $\tau_f$  for all  $f \in \mathcal{F}$ . We are also given estimates of the energy costs (for CBR) or achievable bit rates (for VBR) for downlink communications from the RSU to vehicle v in time slot t, i.e.,  $\epsilon_{v,t}$  (for CBR) or the available bit rate in frame f (for VBR),  $B_{v,f}$ . The scheduler is also given estimates are within multihop forwarding range.
- **OUTPUT:** A scheduler output gives an RSU-to-vehicle transmission schedule. Given the inputs discussed above, the objective of the scheduler is to find a downlink transmission schedule such that all vehicle communication requirements are satisfied, and the downlink RSU energy cost is minimized. In the CBR case this is accomplished by minimizing the total downlink energy needed. In the VBR case the scheduler minimizes the total time needed to fulfill all downlink vehicular transmissions.

The schedules that are generated can be either offline or online. In offline scheduling, the complete set of past and future inputs is provided to the scheduler. Offline scheduling is used in Section 3.2 to obtain lower bounds on energy performance which are used for comparisons with online algorithms. In online scheduling the inputs are
provided to the scheduler in real time and it must create a schedule in real time using these causal inputs. Online scheduling algorithms are given in Chapter 4. In the following section, we formalize these definitions and derive offline bounds on the energy needed for RSU-to-vehicle communication, for both the CBR and VBR cases.

### **3.2** Offline Energy Scheduling Bounds

#### 3.2.1 Constant Bit Rate (CBR) Energy Bound

In this section we present an integer linear programming (ILP) formulation which can be used to find a lower bound on the energy needed for the time-slotted CBR case. It is clear from the example shown in Figure 3.1 that if  $d_v \gg d_w$ , the downlink RSU energy cost associated with multihop communication may be much less than that for direct RSU-to-vehicle communication. This will be so if the energy cost of the RSU-to-vehicle w link is lower than that for vehicle v since the vehicle-tovehicle hop does not affect the RSU energy consumption<sup>2</sup>. For this reason, the RSU prefers to communicate with nearby vehicles rather than more distant ones. However, this scheduling must be done in a way which guarantees that the packet reception requirements of the vehicles are satisfied.

Given an input sample function of arriving vehicles with known speed and traffic requests, the objective is to define an energy efficient algorithm which will schedule downlink transmissions. For a given input sample function, a lower bound is formulated for the energy needed to satisfy downlink vehicular requests. We assume that there are V vehicles indexed by the set  $\mathcal{V} = \{1, 2, \dots, V\}$  and there are T time slots

<sup>&</sup>lt;sup>2</sup>Since the vehicular radios operate from the vehicle engine, they are usually assumed to have unlimited energy reserves.

given by the set  $\mathcal{T} = \{1, 2, ..., T\}$  over which the scheduling is to take place.  $R_v$  is defined to be the communication requirement for vehicle v in bits. We first define the following set of binary scheduling variables.

$$x_{w,v,t} = \begin{cases} 1 & \text{If the RSU sends indirectly to vehicle } v \text{ via direct} \\ & \text{transmission to vehicle } w \text{ in time slot } t \\ 0 & \text{Otherwise} \end{cases}$$
(3.1)

Note that when  $x_{v,v,t} = 1$ , the RSU transmits directly to vehicle v in timeslot t, i.e., without any multihop communication. We also define  $\tau_{v,w}$  to be the set of time slots for which vehicles v and w are within V2V forwarding range and  $\epsilon_{v,t}$  is the single time slot energy cost of downlink communication to vehicle v at time t. The inputs to the problem are therefore given by the set of n-tuples

$$\mathcal{I} = \{ (R_v, \epsilon_{v,t}, \tau_{v,w}) \} \quad \forall v, w \in \mathcal{V}, \, \forall t \in \mathcal{T}$$
(3.2)

and a lower bound on total energy use can be computed using the following integer

linear program (ILP).

$$\underset{x_{w,v,t}}{\text{minimize}} \quad \sum_{t \in \mathcal{T}} \sum_{v \in \mathcal{V}} \sum_{w \in \mathcal{V}} \epsilon_{w,t} \; x_{w,v,t} \tag{CBR-BOUND}$$

$$\sum_{w \in \mathcal{V}} \sum_{t \in \tau_{w,v}} x_{w,v,t} = \lceil R_v / B \rceil, \quad \forall w \in \mathcal{V}$$
(3.3)

$$\sum_{v \in \mathcal{V}} \sum_{w \in \mathcal{V}} \sum_{t \notin \tau_{v,w}} x_{w,v,t} = 0, \qquad (3.4)$$

$$\sum_{v \in \mathcal{V}} \sum_{w \in \mathcal{V}} x_{w,v,t} \le 1, \qquad \forall t \in \mathcal{T} \qquad (3.5)$$

$$x_{w,v,t} \in \{0,1\}, \qquad \forall v, w \in \mathcal{V}, \forall t \in \mathcal{T} \qquad (3.6)$$

In CBR-BOUND, the objective function is simply the downlink energy used by the RSU, i.e., via first-hop transmission from the RSU to vehicle w. Constraint 3.3 ensures that vehicle communication requirements are fulfilled by summing the appropriate values of  $x_{w,v,t}$  but only over the time intervals for which vehicles v and w are within forwarding range. The values of  $x_{w,v,t}$  when  $t \notin \tau_{v,w}$  are set to zero as shown in Constraint 3.4. Constraint 3.5 ensures that a given time slot can contain at most one transmission. Note that in CBR-BOUND we have assumed that V2V forwarding occurs on a separate communication channel from that which is used for RSU-to-vehicle transmission.

CBR-BOUND can be solved directly using branch and bound techniques, and CPLEX has been used with data generated from MATLAB. These results are used for comparisons with on-line algorithms to be introduced in Chapter 4.

#### 3.2.2 Dynamic Network Flow Graph (DNFG) Energy Bounds

The formulation in Section 3.2.1 computes an energy bound for CBR downlink scheduling where vehicle-to-vehicle relaying occurs on a channel which is separate from that used for V2I communication. This result however, is clearly also a lower bound on energy use when V2V and V2I communication occurs over the same channel. In this section we formulate a more complex energy bound that can be used in both the CBR and VBR cases that also includes in-channel V2V forwarding. The formulation uses dynamic network flow graphs (DNFGs) (Kotnyek, 2003).

Unlike static network flow problems, dynamic network flow graphs model the temporal evolution of the static case and can account for flow storage. This is done by modeling the system as a sequence of frames in time. In the general case, the frames can be variable in length, where  $\tau_f$  is the duration of frame f, as discussed in Section 3.1.  $\mathcal{F} = \{1, 2, \ldots, F\}$  is defined to be the set of all frames to be scheduled. A simple illustration of how DNFGs are used for our problem is shown in Figure 3.2 and described in detail in the figure caption. This example shows three frames and three vehicles, numbered 1, 2 and 3. The DNFG shows the evolution of RSU and vehicular connectivity from one frame to the next. The vertical edges connect different time instances of the same vehicle and are used to model the carrying of flow forward in time. In the figure, vehicles 1 and 3 are communicated to directly from the RSU, whereas vehicle 2 receives its flow from vehicle-to-vehicle communications through vehicles 1 and 3.



Figure 3.2: Dynamic Network Flow Graph (DNFG). In this example, only three frames and three vehicles are shown. The graph is directed, with the direction of the vertical edges being from top to bottom and the horizontal edges between vehicles being bi-directional. Node D is the sink.  $RSU_f$  is defined to be the RSU node in frame f and  $V_{i,f}$  is defined to be the vehicle i node in frame f. The edges emanating from the RSU nodes have a cost  $c_{i,f}$  which is equal to the *reciprocal* of the bit rate that the RSU can use to communicate with vehicle i in frame f. All other edge costs are zero. Vehicles 1, 2 and 3 require 5, 10 and 10 units of flow, in bits, respectively. The arrows show those graph edges which are carrying non-zero units of flow. In frame 1, 25 units of flow arrive at the RSU which transmits 15 to vehicle 3. Ten of these are destined for vehicle 3 and the other 5 are destined for vehicle 2. Similarly, in frame 3, the RSU transmits the remaining 5 units of flow directly to vehicle 1. Note that the use of vertical graph edges correspond to the act of storing flow at the associated node, and carrying it forward in time. In frame 1, 5 units of flow for vehicle 2 are sent via vehicle 1, which is forwarded by V2V communications to vehicle 2 in frame 2. Similarly, in frame 2, vehicle 3 forwards 5 units of flow to vehicle 2. In this example, vehicle 2 is provided for solely by V2V forwarding.

In the DNFG formulation, we model flow in units of bits. As before, we define  $\mathcal{V} = \{1, 2, \dots, V\}$  to be the set of vehicles and  $R_v$  is the demand for vehicle v.  $z_{v,f}$  is the number of bits sent from the RSU to vehicle v in frame f.  $y_{i,j,f}$  is defined to be the number of bits sent from vehicle i to vehicle j in frame f. We will first show the variable bit rate case, and therefore we define  $B_{v,f}$  to be the bit rate available between the RSU and vehicle v in frame f.  $B_{i,j,f}$  is the bit rate available between vehicles i and j in frame f. Given these definitions, the DNFG optimization is written as follows.

$$\underset{z_{v,f},y_{i,j,f}}{\text{minimize}} \quad \sum_{f \in \mathcal{F}} \sum_{v \in \mathcal{V}} z_{v,f} / B_{v,f}$$
(DNFG-BOUND)

subject to

$$\sum_{v \in \mathcal{V}} z_{v,f} / B_{v,f} + \sum_{i \in \mathcal{V}} \sum_{j \in \mathcal{V}} y_{i,j,f} / B_{i,j,f} \le \tau_f, \qquad \forall f \in \mathcal{F}$$

(3.7)

$$\sum_{f=1}^{\theta-1} (z_{v,f} + \sum_{i \in \mathcal{V}} y_{i,v,f}) - \sum_{f=1}^{\theta} \sum_{j \in \mathcal{V}} y_{v,j,f} \ge 0, \qquad \forall v \in \mathcal{V}, \forall \theta = \{1, 2, \dots, F\}$$

$$\sum_{f \in \mathcal{F}} (z_{v,f} + \sum_{i \in \mathcal{V}} y_{i,v,f}) - \sum_{f \in \mathcal{F}} \sum_{j \in \mathcal{V}} y_{v,j,f} = R_v, \qquad \forall v \in \mathcal{V}$$

(3.9)

$$z_{v,f} \ge 0, \qquad \qquad \forall v \in \mathcal{V}, \forall f \in \mathcal{F}$$

(3.10)

$$y_{i,j,f} \ge 0,$$
  $\forall i, j \in \mathcal{V}, \forall f \in \mathcal{F}$ 

$$(3.11)$$

The objective minimizes the total time needed by the RSU for downlink transmission. Constraint 3.7 ensures that the number of bits transmitted in each frame, f, does not exceed the frame duration,  $\tau_f$ . The next three are flow conservation constraints. Constraint 3.8 ensures that for each vehicle v, the total number of bits vehicle vforwards to other vehicles by the end of frame  $\theta$  must not exceed the number of bits that were received by v by the end of frame  $\theta - 1$ . The inequality permits a given vehicle to hold bits and carry them forward into future frames. Constraint 3.9 makes sure that at the end of the total time period, the difference between the flow into each vehicle node v and the flow out is the number of bits in its demand,  $R_v$ .

Note that only trivial changes to the above LP are needed to model the in-channel fixed bit rate, variable packet length, case. Since the bit rates are fixed we define  $B_{v,f} \triangleq B$ , for all v and f. The objective will become

$$\underset{z_{v,f}}{\text{minimize}} \sum_{f \in \mathcal{F}} \sum_{v \in \mathcal{V}} z_{v,f} \epsilon_{v,f}$$
(3.12)

where  $\epsilon_{v,f}$  is redefined as the per bit energy cost of transmitting to vehicle v in frame f. Constraint 3.7 will become

$$\sum_{v \in \mathcal{V}} z_{v,f} + \sum_{i \in \mathcal{V}} \sum_{j \in \mathcal{V}} y_{i,j,f} \le B\tau_f, \quad \forall f \in \mathcal{F}$$
(3.13)

Constraints 3.8 to 3.11 remain unchanged.

The above formulations permit the computation of offline bounds on the energy needed for the air interface assumptions that have been considered. They can also be used as a starting point for online algorithms which are discussed in the next chapter.

## Chapter 4

# **Online Scheduling Algorithms**

Chapter 3 gives offline bounds on the RSU energy needed to fulfill vehicular packet requirements. In this chapter we propose online algorithms which perform the required scheduling in real time. In the online case, the scheduling decisions can only be made using data consisting of past and current inputs.

In order to compute the bounds, the energy costs associated with a given packet transmission,  $\epsilon_{v,t}$ , must be known. Although it is difficult to know this information in general, in certain scenarios excellent estimates of this cost can be readily made (Wang, 2005; C. Sommer and Dressler, 2011). For this reason, we consider a highway situation where vehicles may travel at different speeds, but maintain their own speed throughout the RSU coverage area (Khabazian and Ali, 2008). When vehicles first enter the RSU coverage area they announce their location, direction and speed, information that is used by the RSU to estimate future energy transmission costs assuming distance dependent exponential path loss propagation (Wang, 2005; C. Sommer and Dressler, 2011).

### 4.1 Constant Bit Rate (CBR)

#### 4.1.1 Greedy Local Optimization Scheduler (GLOA)

In the basic GLOA scheduler, vehicle-to-vehicle forwarding is assumed to occur on a separate channel than the one used for RSU-to-vehicle transmission. To accomplish this, arriving vehicles are formed into groups for combined RSU-to-vehicle and vehicle-to-vehicle forwarding. We consider the case where at some time instant a group of vehicles has been identified for scheduling. The scheduling is based on a greedy local optimization defined below. We denote by  $\mathcal{G}$  the group of vehicles that will be scheduled and will engage in hybrid RSU-to-vehicle and vehicle-to-vehicle forwarding,  $\mathcal{K}$  by the set of time slots *currently available* to the vehicles in set  $\mathcal{G}$ , i.e., the set of unscheduled time slots,  $H_i$  the transmission requirement for vehicle *i* in time slot *k*. We would like to minimize the energy needed to process this group of vehicles, i.e.,

$$\underset{x_{i,k}}{\text{minimize}} \qquad \sum_{i \in \mathcal{G}} \sum_{k \in \mathcal{K}} x_{i,k} \epsilon_{i,k}$$
(4.14)

subject to 
$$\sum_{k \in \mathcal{K}} x_{i,k} \ge H_i \quad \forall i \in \mathcal{G}$$
 (4.15)

$$\sum_{i \in \mathcal{G}} x_{i,k} \le 1 \qquad \forall k \in \mathcal{K}$$
(4.16)

$$x_{i,k} \in \{0,1\}$$
  $\forall i \in \mathcal{G}, \forall k \in \mathcal{K}$  (4.17)

Note that

$$\min_{x_{i,k}} \sum_{k \in \mathcal{K}} \sum_{i \in \mathcal{G}} x_{i,k} \epsilon_{i,k}$$
(4.18)

$$\geq \min_{x_{i,k}} \sum_{k \in \mathcal{K}} \min_{i \in \mathcal{G}} \{\epsilon_{i,k}\} \sum_{i \in \mathcal{G}} x_{i,k}$$
(4.19)

$$= \min_{x_{i,k}} \sum_{k \in \mathcal{K}} \mathcal{E}_{\mathcal{G},k} X_{\mathcal{G},k}$$
(4.20)

where we have defined  $X_{\mathcal{G},k} = \sum_{i \in \mathcal{G}} x_{i,k}$  and  $\mathcal{E}_{\mathcal{G},k} = \min_{i \in \mathcal{G}} \{\epsilon_{i,k}\}$ . Also note that  $X_{\mathcal{G},k} \leq 1 \ \forall k \in \mathcal{K}$ . Since we allow vehicle-to-vehicle forwarding for group  $\mathcal{G}$ , we can aggregate the time slots needed by this group, and interpret  $X_{\mathcal{G},k}$  as

$$X_{\mathcal{G},k} = \begin{cases} 1 & \text{if the RSU transmits to vehicle group } \mathcal{G} \\ & \text{in time slot } k, \\ 0 & \text{otherwise,} \end{cases}$$
(4.21)

and the optimization can then be written as

$$\underset{X_{\mathcal{G},i}}{\operatorname{minimize}} \qquad \sum_{k \in \mathcal{K}} X_{\mathcal{G},k} \ \mathcal{E}_{\mathcal{G},k} \tag{GROUP-OPT}$$

subject to 
$$\sum_{k \in \mathcal{K}} X_{\mathcal{G},k} \ge \sum_{i \in \mathcal{G}} H_i$$
 (4.22)

$$X_{\mathcal{G},k} \in \{0,1\} \qquad \forall k \in \mathcal{K}$$

$$(4.23)$$

The optimization GROUP-OPT reflects the fact that due to vehicle-to-vehicle sharing, the time slot available for use by a vehicle at time k incurs an RSU energy cost which is the minimum of the costs for all vehicles in the group. This is where the RSU energy advantage is obtained. For this reason the optimization need only allocate  $\sum_{i \in \mathcal{G}} H_i$  of these time slots. This optimization can be easily solved by sorting the set

$$\{\min_{i\in\mathcal{G}}\{\epsilon_{i,k}\}\}\tag{4.24}$$

for all k in increasing order of energy cost and then by allocating those time slots corresponding to the first  $\sum_{i \in \mathcal{G}} H_i$  entries.

If the group  $\mathcal{G}$  consists of vehicles which are platooning together at the same speed, then there is very little energy gain to be made even if their job requirements are different. i.e., for a given k the minimum in Equation 4.24 is the same for all vehicles. The groups that are formed must instead give the system "diversity in energy". In the special case where vehicles travel at the same speed but are not platooning and have different job sizes, energy improvements are possible. For example, consider the case where  $\mathcal{G}$  consists of 2 vehicles,  $V_1$  and  $V_2$ . Also, assume that the system is lightly loaded so that all time slots are available. If the vehicles are sufficiently separated, then the set of  $H_1 + H_2$  time slots where  $\sum_{k \in \mathcal{K}} \min_{i \in \mathcal{G}} \{\epsilon_{i,k}\}$  is minimized will be those time slots where  $V_1$  and  $V_2$  are closest to the RSU i.e., we can view the solution as the same as the case for two vehicles traveling in a disjoint fashion, each having a job size of  $(H_1 + H_2)/2$ .

The intuition above motivates the proposed scheduling algorithm, GLOA, as shown in Algorithm 1. The idea is that the energy costs for a vehicle group can be the minimum energy cost of all the group's vehicles, but these costs are time varying as the group moves through the RSU coverage area. However, note that the time that a fast moving vehicle spends in energy favourable locations is proportionately less than that of a slow moving vehicle in the same group. For this reason when

Algorithm 1 Greedy Local Optimization Scheduler (GLOA)
1: for all $t \in \{0, 1,\}$ do
2: <b>if</b> a vehicle $v$ arrives to the system <b>then</b>
3: Find the largest vehicle group currently within RSU coverage range, $\mathcal{G}$ , such
that for all vehicles $w \in \mathcal{G}, \{t, t+1, \ldots, T_c\} \subset \tau_{v,w}$ , where $\tau_{v,w}$ is the set
of time slots for which vehicles $v$ and $w$ are within multihop communication
range and $T_c$ is a target contact duration, i.e., all vehicles in $\mathcal{G}$ remain within
V2V communication range with $v$ for a time duration $T_c$ .
4: Define $H_T$ to be the total residual backlog for the vehicles in $\mathcal{G}$ , i.e., $H_T =$
$\sum_{i \in \mathcal{G}} H_i$ where $H_i$ is the residual backlog for vehicle <i>i</i> .
5: Assign the $\widetilde{H}_T$ backlog across the vehicles in $\mathcal{G}$ in proportion to each vehicle's
relative speed, i.e., vehicle <i>i</i> is assigned a backlog fraction of $1/S_i \sum_{i \in G} (1/S_i)$ ,
where $S_i$ is the speed of vehicle <i>i</i> .
6: Time slots are allocated using an earliest-RSU-arrival (ERA) prioritization.
7: end if
8: end for

the total remaining vehicular backlog is distributed across the group, it is done in decreasing proportion of vehicle speed.

Referring to Algorithm 1, GLOA operates as follows. When a vehicle v arrives at time t, a vehicle group is found such that vehicle-to-vehicle communications is possible for a contact duration time  $T_c$ . This is shown in Steps 1 to 3. If a group cannot be found then the vehicle initiates a new vehicle group of its own. In Step 4 the total residual backlog for the group is determined. This consists of the total number of remaining time slots needed for the group, denoted by  $\tilde{H}_T$ . This is "assigned" across the vehicles in the group based on vehicle speed as shown in Step 5. Vehicles with lower speed are assigned a proportionately larger fraction of the total residual backlog, and the computations shown are truncated to the appropriate integer slot times. Note that this is a "virtual assignment" in that a time slot needed for vehicle i which is "assigned" to vehicle j means that the RSU communicates that packet to vehicle i through multi-hop forwarding via vehicle j. In the case where all vehicles in  $\mathcal{G}$  are traveling at the same speed, the remaining backlog will be distributed uniformly across all  $|\mathcal{G}|$  vehicles in the group. Finally, in Step 6 the vehicle demands are allocated across the desired time slots in order of earliest-RSU-arrival (ERA) priority, which is an energy efficient schedule; it is precisely the grouping of vehicles that V2V permits which allows this scheduling.

## 4.1.2 GLOA with Minimum Cost Flow Graph Scheduling (GLOA-MCFG)

This algorithm is a more sophisticated version of GLOA, where step 6 is replaced with a minimum cost flow graph (MCFG) scheduler discussed in reference (Hammad *et al.*, 2010). Although this scheduler is more complex, the schedule can be generated in time which is polynomial in the number of time slots to be scheduled. This algorithm is referred to as GLOA-MCFG.

#### 4.1.3 Finite Window Group Optimization (FWGO)

More sophisticated schedulers than the GLOA versions can be obtained by solving an ILP at each vehicular arrival over a finite window period consisting of the union of time slots for which the current set of vehicles is within RSU coverage. When a new vehicle v arrives, the algorithm proceeds as in Algorithm 1 up to and including step 3. However, the timeslot assignment is done using a minimum cost flow graph scheduler (Hammad *et al.*, 2010; Ahuja *et al.*, 1994) using a simplification of CBR-BOUND, which is possible when the vehicle groups are constant throughout the time window considered. First we define  $\mathcal{G}_v$  to be the vehicle group for vehicle v as discussed in Section 4.1.1. Taking the objective function from CBR-BOUND and noting that Algorithm 2 Finite Window Group Optimization (FWGO)

- 1: for all  $t \in \{1, 2, ...\}$  do
- 2: if a vehicle v arrives to the system then
- 3: Find the largest vehicle group currently within RSU coverage range,  $\mathcal{G}_v$ , such that for all vehicles  $w \in \mathcal{G}$ ,  $\{t, t + 1, \ldots, T_c\} \subset \tau_{v,w}$  where  $T_c$  is a target contact duration, i.e., all vehicles in  $\mathcal{G}_v$  remain within V2V communication range with v for a time duration  $T_c$ . (This is the same as step 3 in Algorithm 1.)
- 4: Define  $\mathcal{V}_t$  to be the current set of vehicles within RSU coverage.
- 5: Solve optimization CBR-BOUND using the residual (unserved) vehicular traffic of vehicles  $\mathcal{V}_t$  to obtain the minimum cost time slot assignments,  $x_{\mathcal{G}_v,t}$ . Note that when vehicles v and w are within V2V communication range for the entire time window, this optimization can be found in time which is polynomial in the number of time slots using a minimum cost flow graph (MCFG) using the construction shown in Figure 4.3.
- 6: Execute the schedule obtained in step 5.
- 7: end if
- 8: end for

 $x_{w,v,t} = 0$  when  $w \notin \mathcal{G}_v$ , the objective of CBR-BOUND can be written as

$$\sum_{t \in \mathcal{T}} \sum_{v \in \mathcal{V}} \sum_{w \in \mathcal{G}w} \epsilon_{w,t} x_{w,v,t}$$
(4.25)

and therefore

$$\sum_{t \in \mathcal{T}} \sum_{v \in \mathcal{V}} \sum_{w \in \mathcal{G}_v} \epsilon_{w,t} x_{w,v,t} \ge \sum_{t \in \mathcal{T}} \sum_{v \in \mathcal{V}} \{ \min_{w \in \mathcal{G}_v} \epsilon_{w,t} \} \sum_{w \in \mathcal{G}_v} x_{w,v,t}$$
(4.26)

$$\triangleq \sum_{t \in \mathcal{T}} \sum_{v \in \mathcal{V}} \epsilon_{\mathcal{G}_v, t} x_{\mathcal{G}_v, t}$$
(4.27)

where  $x_{\mathcal{G}_v,t} \triangleq \sum_{w \in \mathcal{G}_w} x_{w,v,t}$  and  $\epsilon_{\mathcal{G}_v,t} \triangleq \min_{w \in \mathcal{G}_v} \epsilon_{w,t}$ . The scheduling is now done in a group-wise fashion where  $x_{\mathcal{G}_v,t}$  is equal to one if the RSU transmits to vehicle group  $\mathcal{G}_v$  during time slot t, and zero otherwise. Similarly,  $\epsilon_{\mathcal{G}_v,t}$  is defined to be the minimum

energy cost available between the RSU and the vehicles in group  $\mathcal{G}_v$ , at time t. The resulting ILP is as follows.

$$\underset{x_{\mathcal{G}_{v,t}}}{\operatorname{minimize}} \qquad \sum_{t \in \mathcal{T}} \sum_{v \in \mathcal{V}} \epsilon_{\mathcal{G}_{v,t}} x_{\mathcal{G}_{v,t}}$$
(FWGO-ILP)

subject to 
$$\sum_{t \in \mathcal{T}} x_{\mathcal{G}_{v,t}} = \widetilde{H}_{v}, \quad \forall v \in \mathcal{V}$$
 (4.28)

$$\sum_{v \in \mathcal{V}} x_{\mathcal{G}_{i,t}} \le 1, \quad \forall t \in \mathcal{T}$$
(4.29)

$$x_{\mathcal{G}_{i},t} \in \{0,1\}, \quad \forall i \in \mathcal{V}, t \in \mathcal{T}$$

$$(4.30)$$

This ILP generates a minimum energy schedule for the inputs used at time t. A major advantage of this approach is that FWGO-ILP can be solved in time which is polynomial in the number of time slots, using a minimum cost flow graph construction (Ahuja *et al.*, 1994). An example of this scheduler is shown in Figure 4.3, where graph G = (V, E) has a set of vertices, V, and a set of edges E (Hammad *et al.*, 2013). Each edge  $(i, j) \in E$  has a capacity  $u_{i,j}$ , and a cost,  $c_{i,t}$ , that denotes the energy penalty paid per unit of flow on that edge. These are written as ordered pairs  $(u_{i,t}, c_{i,t})$  on each graph edge.



Figure 4.3: Minimum Energy Vehicle Group Flow Graph Scheduler. Each edge is labeled with an ordered pair,  $(u_{i,t}, c_{i,t})$ , where  $u_{i,t}$  and  $c_{i,t}$  are the capacity and cost of using edge (i, t). The input and output nodes, I to O, carry a flow of  $\sum_{v \in \mathcal{N}} \tilde{H}_v$ . They are connected to the rest of the graph by zero cost edges.

The flow enters and exits the graph at source and collection nodes S and D. The first column of nodes represents all N currently active vehicle groups. The second column represents all time slots  $\mathcal{T}_t$ , where  $T = |\mathcal{T}_t|$ . Each vehicle group node has edges connected to the time slot nodes during which vehicles in that group are inside the RSU coverage area with a cost,  $\epsilon_{\mathcal{G}_v,t}$ , which is the minimum of the RSU to vehicle costs for group v as defined above. The capacity for an edge from the source S to a vehicle node is the residual communication requirement for vehicle v in time slots, denoted by  $\widetilde{H}_v$ .

The capacity for an edge from any time slot node to the destination D is 1, which prevents time slots from being used more than once. The edges between a vehicle *i* and the time slots also have a capacity of 1, which ensures that only one unit of transmission requirement can be assigned to a given time slot. The cost for the edges originating from S or terminating at D is zero. Finding the minimum cost flow for graph G provides the minimum energy the RSU must consume to schedule vehicle transmission requirements for the given set of inputs. The Integrality Property (Ahuja *et al.*, 1994) ensures that when the demand and capacities are integer, there is an integer minimum cost flow. Since our vehicle groups to time slot edge capacities are 1, the resulting flow paths are binary and give the values  $x_{\mathcal{G}_v,t}$  which achieve minimum energy.

## 4.1.4 In-Channel V2V Scheduling (GLOA-IC, GLOA-MCFC-IC and FWGO-IC)

The algorithms introduced in sections 4.1.1, 4.1.2 and 4.1.3 assume that the V2V relaying occurs on a separate channel than that of V2I communications, i.e., the offchannel forwarding case. We also consider in-channel V2V forwarding where vehicleto-vehicle relaying occurs on the same channel. In this case the algorithms are identified by appending "-IC" (in-channel) to the algorithm name.

In GLOA-IC and GLOA-MCFG-IC, at each vehicle arrival time we execute the algorithms as discussed in Sections 4.1.1 and 4.1.2. However, once time slots have been assigned for RSU-to-vehicle transmission, they are excluded from consideration and V2V time slots are assigned using a simple higher-speed-first prioritization. In a similar way, FWGO-IC executes the FWGO Algorithm as given in Section 4.1.3. Following this, the assigned V2I time slots are excluded and V2V time slots are assigned as in the GLOA-IC algorithm.

### 4.2 Variable Bit Rate (VBR)

In this section we adapt the algorithms introduced in Section 4.1 for use in the variable bit rate air interface case. This involves minor changes to how the algorithms operate, which are discussed below.

#### 4.2.1 GLOA, VBR Version (GLOA-VBR)

This algorithm is a variation of GLOA applied to the VBR case. The steps shown in Algorithm 1 are followed exactly except that time is allocated for each vehicle using higher bits rates associated with that vehicle and time whenever possible.

#### 4.2.2 FWGO, VBR Version (FWGO-VBR)

The algorithm given in Section 4.1.3 is followed exactly except that time is allocated for each vehicle in accordance with the bit rate associated with that vehicle and time. The assignment to frames is done based on the dynamic flow graph formulation discussed in Section 3.2.2.

An issue which may arise in both the GLOA-VBR and FWGO-VBR algorithms has to do with the nature of the output obtained from the dynamic flow graph formulation. A difference between the CBR and VBR models presented in Sections 3.2.1 and 3.2.2 respectively, is that the (VBR) dynamic flow formulation gives output which is fractional. This is fine since our units of flow in the VBR case are in bits, so for the online algorithms, the fractional output can be simply rounded to the nearest integer. However, an issue which may arise is that the number of bits assigned to a given frame may be below a desired minimum packet length. We have found that for

Algorithm 3 FWGO, VBR Version (FWGO-VBR)
for all $v \in \{\mathcal{V}\}$ do
if a vehicle v arrives to the system then
find a vehicle group, G, such that all vehicles in Gwill remain within V2V
communication range with $v$ for a target vehicle contact duration, $T_c$
Based on the position and speed make frames and frame length, also find Bit
rate for each vehicle in the frames.
Solve the LP - Dynamic Flow Graph
end if
end for

parameters of interest, this rarely happens, but when it does, the VBR algorithms take the assigned bits, rounds them up to the minimum packet length and transmits them in the first available frame where they can be accommodated. This frame may, of course, be in a less energy favorable location than that where the bits were originally assigned.

### 4.2.3 GLOA-IC and FWGO-IC, VBR Versions

Just as we consider in-channel forwarding for the CBR case, the same goes for the VBR case. GLOA-IC-VBR is the same algorithm proposed in Section 4.2.1. In GLOA-IC, however, after scheduling V2I transmissions, the scheduler will put aside frame times allocated for RSU-to-Vehicle communication and then assign V2V communications using the remaining capacity. The same goes for the FWGO-IC-VBR algorithm.

## Chapter 5

# Results

In this section the performance of the proposed algorithms is investigated. A wide variety of experiments have been performed, and we will present samples which are representative of the results that we have obtained. The input data to the schedulers is taken from a highway environment where vehicles are assumed to maintain constant speed throughout the RSU coverage areas (Khabazian and Ali, 2008; Hammad *et al.*, 2013). It has been shown that in this type of scenario, good estimates of energy costs can be readily made (Wang, 2005; C. Sommer and Dressler, 2011). The associated energy cost inputs are based on vehicle position and associated estimates of downlink transmission energy costs. We assume that the energy costs come from a distance dependent exponential path loss model with a path loss exponent of  $\alpha = 3$ . However, in many practical systems there will be dominant deterministic propagation with random components due to effects such as shadowing. Therefore, we also include results which incorporate errors due to strong shadowing components. The models used assume Poisson process vehicle arrivals as in (Wang, 2005; Khabazian and Ali, 2008; Bilstrup *et al.*, 2008). We also assume that  $T_c$  is set to the transit time of



Figure 5.1: Total RSU Downlink Energy Vs Vehicular Density (Vehicle per km). In this experiment the speed is constant and equal to 20 m/sec for all the vehicles. The job sizes were taken from a Gaussian distribution with mean 5 (needed time slots) and a standard deviation of 2.

the given vehicle through the RSU coverage area. In the VBR simulation, the IEEE 802.11p standard has been used for selecting the bit rates.

In Figure 5.1 the total downlink RSU energy use is plotted versus vehicular density for the constant bit rate case. The graph includes results for the offline bounds derived in Section 3.2 and we have included these bounds for the cases with and without V2V forwarding. It can be seen from the graph that vehicle-to-vehicle forwarding can significantly decrease the RSU energy needed, especially as vehicle density becomes higher. For example, when comparing the simple GLOA algorithm with and without V2V forwarding (GLOA vs GLOA w/o V2V) we find that the energy use without V2V



Figure 5.2: Total RSU Downlink Energy Vs Vehicular Density (Vehicle per km). In this experiment the job sizes of all the vehicles are constant and equal to 5 (time slots), and the speed is taken from a Gaussian distribution with a mean 20 m/sec and the standard deviation of 2.

is about 100% higher at the largest vehicle density shown. When doing the forwarding in-channel (GLOA-IC), there is typically a slight loss in energy efficiency due to the contention for downlink time slots. At the value of density quoted above, the downlink energy for GLOA-IC is about 20% higher than the off-channel case. The graph also shows that by combining V2V forwarding with a much more sophisticated time slot assignment algorithm (i.e., GLOA-MCFG and GLOA-MCFG-IC), the energy efficiency can be improved significantly. For example, the GLOA-MCFG algorithm requires less than 50% less energy than basic GLOA at the higher vehicular density. As before, when requiring the algorithm to schedule the V2V transmissions in-channel, a small energy penalty is paid. The best performance was obtained by the FWGO algorithms (FWGO and FWGO-IC) and we can see that their energy requirements are about 100% above the offline bound. This is quite good, considering how poor the other algorithms perform compared with the offline bound. Clearly the more sophisticated algorithms are closer to the bounds, as expected.

It is possible to operate some of the non-V2V schedulers using the more complex MCFG time slot assignment. In the interests of clarity we have not include results for these cases in the figures. However, we have included the offline bound for the non-V2V case from Section 3.2 (shown as "BOUND w/o V2V"). In practice, the best online algorithms perform somewhat above this bound, and it can be seen that the best algorithms with V2V forwarding perform significantly below it. At the highest vehicular density shown in Figure 5.1, for example, the bound gives an energy value which is over 400% higher than the online FWGO algorithm. Clearly, V2V forwarding can significantly decrease RSU energy use even if an online algorithm without V2V forwarding could achieve the offline bound.

We now consider the advantages of V2V forwarding when there are differences in vehicle speed assuming there is no multi-cast. First consider the case where two vehicles are moving in the same direction with the same speed, and therefore they will be at a constant distance relative to each other. If there is no difference in the vehicular job sizes, then it is easy to see that there is no energy advantage to vehicle-to-vehicle forwarding. Now consider the case where one of the vehicles is traveling at a much higher speed than the other. The fast moving vehicle will be at the most energy favorable locations, e.g., closer to RSU, for less time than the slower moving vehicle. Assuming the vehicles maintain contact, vehicle-to-vehicle



Figure 5.3: Total RSU Downlink Energy Vs Job Sizes Mean. In this experiment the Vehicular Density is constant and equal to 4 vehicle per km, the job sizes come from a Gaussian Distribution with Standard Deviation of 2

forwarding can play a significant role in improving energy efficiency. Figure 5.2 uses the same parameters as Figure 5.1, except that we have drawn the speed of each vehicle from a Gaussian distribution, as discussed in the figure caption. It is clear that the vehicle speed differences will increase the advantage of vehicle-to-vehicle forwarding. However, the benefit of V2V forwarding is not comparable with the previous case when there were differences in job sizes. For example, GLOA with and without V2V forwarding shows about a 30% advantage at highest vehicular density comparing to around 100% in case of figure 5.1. Contrary to Figure 5.1, where GLOA-MCFG was doing better than the Bound w/o V2V, in this figure it is worse by about



Figure 5.4: Total RSU Downlink Energy Vs Job Size Standard Deviation. In this experiment the job size mean is constant and equal to 5, vehicular density is constant and equal to 4 vehicle per km and vehicle speed is constant and equal to 20 m/sec.

20%. This is due to the decrease in advantage that vehicle speed differences make. It should be noted that the GLOA-MCFG w/o V2V algorithm would be somewhere above the Bound w/o V2V. Also, the FWGO algorithm is doing the best compared to the other online algorithms, as before. Both FWGO and FWGO-IC algorithms are below the Bound w/o V2V by about a 60% advantage, and they are both quite close to Bound with V2V, i.e., off by about 25% which is very good compared to the other online algorithms. This plot shows the pure performance of GLOA and GLOA-MCFG, assigning time slots based on relative speed in a greedy fashion.



Figure 5.5: Total RSU Downlink Energy Vs Vehicular Density (Vehicle per km). This plot has the same assumptions as 5.1 with added shadowing. We used a log normal shadowing

The benefits of vehicle-to-vehicle forwarding come from differences in vehicle speed, job sizes and system loading. Figure 5.3 shows that as the vehicle job sizes increase, the benefit of V2V forwarding becomes more pronounced. The reason for this advantage is clearly because, in the non-V2V case, traffic must be transmitted in less energy favourable situations. If the system load remains constant, as the variation in job sizes increases, it is expected that the energy use with smart V2V forwarding would remain constant. In a system with no V2V communication, increases in energy would be expected. This phenomenon is the focus of Figure 5.4. In Figure 5.3 the effects of the average job size is shown and the advantage of V2V forwarding with the increase in loading is obvious. In Figure 5.3 all the points have the same standard deviation, unlike Figure 5.4, in which the mean is the same. It is clear from this example that the increase in variation makes V2V forwarding more advantageous. For example, at the lowest standard deviation, i.e., 1, the Bounds with and without V2V forwarding differ by about 70% whereas at a standard deviation of 3, the Bound with V2V forwarding is almost 10 times better than the Bound without V2V case. This is a large difference in energy usage which can also be seen in the online algorithms. For example, GLOA with V2V is 2 times better than without V2V. Also, FWGO and FWGO-IC, GLOA-MCFG and GLOA-MCFG-IC, are all are doing better than the Bound without V2V (and any non-V2V scheduler). FWGO is about 4 times better than Bound w/o V2V. Also, it is expected that increases in variation will not affect energy usage when there is V2V forwarding. This can be seen in Figure 5.4 where Bound with V2V only increases by about 10% while Bound w/o V2V increases by almost 275%. The better the online algorithm, the less increase in energy use is expected as the variation in job sizes increases. As an example, FWGO only increases by 75%, GLOA-MCFG increases by about 80%, and simple GLOA experiences a 75%increase. This result with only 10% increase compared to the Bound, shows better time slot usage.

Figure 5.5 uses the same assumptions as in Figure 5.1 except that the energy cost data that is fed to the schedulers includes random components. This is done to ensure that when the scheduler input data are not ideal, the algorithms do not produce results which would be biased in some way, due to this randomness. In the results presented, this was done by adding propagation shadowing effects to the extracted data, which result in unpredictable randomness in these estimates. The



Figure 5.6: RSU downlink Transmission Time Vs Vehicular Density. In this experiment we have a distribution for the job sizes such that 85% of vehicles have no job, but the other 15% have a large job size. In this experiment we chose the speed of the vehicle to be equal.

scheduling is therefore based on this input, but the actual costs incurred include the energy perturbations due to the random components. It can be seen in Figure 5.5 that the same relative performance comparisons are true for this case except that the energy values obtained are higher. For example, the RSU energy cost for the basic GLOA algorithm is about double what it was before. The same may be said for the other algorithms and offline bounds. As was illustrated earlier, on-line algorithms use knowledge of vehicle position as well as downlink energy costs. However these estimations could include errors, due to randomness of the wireless channel. In the presence of such complications, as was shown in Figure 5.5, the difference between



Figure 5.7: RSU Downlink Transmission Time Vs Job Size, The same characteristics as the figure 5.6 but the job sizes now changing, vehicular density is all equal to 4 vehicle per km.

the on-line algorithms and Bound becomes wider, as the Bound has prior knowledge, whereas the online algorithms schedule vehicles based on ideal energy estimations accumulated up to the present.

Figures 5.6 to 5.8 are samples of experiments conducted in the VBR case. In Figure 5.6 the total RSU downlink transmission time is plotted versus vehicular density. As the vehicular density increases, the benefit of vehicle-to-vehicle forwarding increases. Clearly all the online algorithms are doing better than the Bound w/o V2V, and the FWGO-VBR OFF channel case at the highest bit rate is using almost 3 times less transmission time. The advantage of FWGO-VBR algorithm over GLOA



Figure 5.8: RSU downlink transmission time Vs Vehicular Density. This plot has the same characteristics as 5.6 with the difference that speed of vehicles have been driven from a gaussian distribution with mean 20 m/s and standard deviation of 2

is apparent as the density increases. It can be seen that FWGO is doing better than FWGO-IC by about 15%, about 25% better than GLOA-DFG and over 70% better than GLOA-DFG-IC. The worst online algorithm for the V2V case, i.e., GLOA-DFG-IC, is doing about 80% better than the Bound w/o V2V. It should be noted that in the case simulated here vehicles have small job sizes, but there is a small fraction of vehicles, i.e., 15% which have large job sizes.

Figure 5.8 uses the same parameters as the previous experiment except that the speed is also variable. As the results from the CBR case have shown, speed variation is one of the reasons vehicle-to-vehicle forwarding is advantageous. Obviously,



Figure 5.9: Total RSU Downlink Energy Vs Vehicular Density (Vehicle per km). The characteristics of this experiment is the same as figure 5.3 but it has been done for shorter time

adding that to the experiment of Figure 5.6 makes the vehicle-to-vehicle forwarding more useful and the differences between V2V online algorithms and the Bound w/o V2V are very obvious. Figure 5.7 shows the effect of job size: as in the CBR case, higher system load results in increased performance with vehicle-to-vehicle forward-ing. At the highest load, there is about a 130% advantage comparing FWGO and the Bound w/o V2V. Although other online algorithms are performing poorly compared to FWGO, they are still far better than Bound w/o V2V. For example, FWGO-IC is doing around 100% better, GLOA-DFG about 110% and GLOA-DFG-IC about 80%.

Finally, Figure 5.9 shows the bound for the CBR case derived from both the

ILP formulation in Section 3.2.1 and dynamic flow formulation in Section 3.2.2. As was previously discussed, there are major differences between the two formulations. First of all, the DNFG formulation has the advantage of being an LP instead of an ILP. Second, the DNFG formulation has multi-hop vehicle-to-vehicle transmission, compared to the ILP bound which only allows one-hop forwarding. Finally, the DNFG formulation allows non-integer solutions. In the result, the bound derived with the DNFG formulation uses a bit less energy compared to the ILP solution which is the focus of Figure 5.9.

In summary, as the vehicular density increases, the number of vehicles in the coverage area also increases, and the benefits from vehicle to vehicle forwarding become more apparent, since there are more vehicles within mutual communication range. In the case where there is no vehicle-to-vehicle communication, it is obvious that by increasing the number of vehicles in the system, the total downlink energy, or equivalently, the transmission time in the VBR case, will increase. At the same time, when intelligent vehicle-to-vehicle forwarding is available, large improvements in energy efficiency are possible. Examples of such improvements have been shown above.

## Chapter 6

# Conclusion

In this thesis we have presented results which show that by combining smart scheduling with vehicle-to-vehicle (V2V) packet forwarding, downlink vehicular infrastructure energy use can be significantly decreased. This happens because vehicles have virtually unlimited energy reserves, and as a result, vehicular forwarding does not incur infrastructure energy costs. Roadside infrastructure can therefore reduce energy use by forwarding packets through vehicles which are in energy favorable locations. Offline bounds were derived for the downlink energy usage when V2V forwarding is used. This includes both the off-channel and in-channel V2V forwarding cases. The in-channel bound uses a formulation based on a dynamic network flow graph model. These bounds were used for comparisons with various online scheduling algorithms where both fixed and variable bit rate air interface options were considered.

The thesis then introduced online algorithms. The first algorithm used a greedy local optimization, referred to as GLOA. A version of this algorithm was also considered which uses a minimum cost flow graph scheduler to perform the time slot assignment. A more complex algorithm was also introduced which is based on a proposed finite window group optimization (FWGO). Versions of these algorithms were introduced which use in-channel vehicle-to-vehicle scheduling, and were also adapted to the variable bit rate air interface case. Results from a variety of experiments show that under certain conditions, the proposed scheduling algorithms can significantly improve the downlink energy requirements of the roadside unit compared to the case where vehicle-to-vehicle packet forwarding is not used. The performance improvements are especially strong under heavy loading loading and when the variation in vehicle communication requirements or vehicle speed is high.

### 6.1 Future Work

In this thesis, only single road side unit (RSU) scenarios were considered. Further work could consider multiple RSUs. Also, rather than total energy consumption, it may be advantageous to appropriately energy balance the multiple RSUs.

In this thesis we have not placed constraints on the service delay, which could also be taken into consideration. Emergency and critical messaging in VANETs with guaranteed QoS requires minimal delay. Hence, more studies should be performed to considering this. Future work could consider minimizing energy consumption while ensuring appropriate levels of QoS.

While energy consumption was the focus of this work, other system parameters have not been considered. Important aspects such as service latency, and saturation throughput could be considered. This is not only specific to this thesis, most of the research in the literature do not consider the network with all its attributes.

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