ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

STORE AND FORWARD SCHEDULING IN CLUSTERED VEHICULAR NETWORKS

M.Sc. THESIS

Salih Serdar GÜÇLÜ

Department of Computer Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

KÜMELENMİŞ ARAÇLAR ARASI AĞLARDA SAKLA VE İLET TİPİ İLETİŞİMLERİN ZAMANLANMASI

YÜKSEK LİSANS TEZİ

Salih Serdar GÜÇLÜ
(504111528)

Bilgisayar Mühendisliği Anabilim Dalı

Bilgisayar Mühendisliği Programı

Tez Danışmanı: Associate Prof. Dr. Deniz Turgay ALTILAR

MAYIS 2014

Salih Serdar GÜÇLÜ, a M.Sc. student of ITU Graduate School of Science Engineering and Technology 504111528 successfully defended the thesis entitled **"STORE AND FORWARD SCHEDULING IN CLUSTERED VEHICULAR NETWORKS"**, which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor :	**Associate Prof. Dr. Deniz Turgay ALTILAR** Istanbul Technical University	....
Jury Members :	**Prof. Dr. Sema Fatma OKTUĞ** Istanbul Technical University	....
	Assistant Prof. Dr. Müjdat SOYTÜRK Marmara University	....
		....

Date of Submission : **5 May 2014**
Date of Defense : **28 May 2014**

To Sıla,

FOREWORD

Since the last year of bachelor of science, I have worked on vehicular networks. I had deep knowledge on vehicular networks from then to now. I would like express my gratitude to my supervisor, Assoc. Dr. D. Turgay Altılar for his excellent guidance and friendliness. I feel honoured to work with him.

I appreciate my brother, my mother and my father for their faith in me.

Finally, I would like to give my special thanks to my dear fianceé, Sıla Özen for her endless support during this journey. Without her, I could not have strength to complete this work.

May 2014

Salih Serdar GÜÇLÜ
(Computer Engineer)

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ABBREVIATIONS

ITS	**:** Intelligent Transport Systems
VANET	**:** Vehicular Ad-Hoc Network
RSU	**:** Road-Side Unit, i.e. infrastructure
V2V	**:** Vehicle to vehicle communication
V2R	**:** Vehicle to Road-Side Unit
R2V	**:** Road-Side Unit to Vehicle
V2V2R	**:** Vehicle to vehicle to RSU communication
R2V2V	**:** RSU to vehicle to vehicle communication
EDF	**:** Earliest Deadline First
FCFS	**:** First Come First Served

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**STORE AND FORWARD SCHEDULING
IN CLUSTERED VEHICULAR NETWORKS**

SUMMARY

Vehicular networks are highly mobile networks which comprise of vehicles and stationary units that are equipped with short range wireless communication devices. Vehicular networks are promising research area to increase driver safety, control vehicular traffic better, enable wider use of infotainment applications and beyond.

Vehicular networks' unique nature separates it from other kind of wireless networks with several new challenging problems. In vehicular networks, multi-hop communications with stationary infrastructure (i.e. road-side unit) is a studied problem. However, utilization of this type of communication is not considered lately. We designed models that can utilize communications between vehicles and road-side units avoiding expensive tools such as cellular communications or directional antennas.

This thesis considers scheduling of vehicle to vehicle to roadside unit (V2V2R) communications in a clustered vehicular ad-hoc network (VANET) in order to improve communication channel utilization. Two novel communication models are proposed to increase amount of data that can be transferred between cluster of vehicles and the roadside unit, where each vehicle has its own data to be transferred. In addition to direct V2R communications, V2V2R communications are effectively employed for this purpose. A store and forward mechanism is used for scheduling V2V2R communications. Proposed model takes advantage of limited and predictable mobility patterns of the vehicles.

It is assumed vehicles constitute a cluster which is a group of vehicles that move towards same direction with slightly similar velocity. Under the control of the cluster head, vehicles which would have idle time while staying in the range of RSU, volunteers to relay other vehicles' data if necessary. V2V2R resource sharing problem is modelled as a linear programming problem without compromising scalability. Simulations proved that the proposed model achieves significantly higher utilization compared to earliest deadline based and first come first served based scheduling algorithms. Presented simulations shows that proposed models are able to almost fully utilizing communication channel.

KÜMELENMİŞ ARAÇLAR ARASI AĞLARDA
SAKLA VE İLET TİPİ İLETİŞİMLERİN ZAMANLANMASI

ÖZET

Araçlar arası ağlar yüksek derecede hareketliliğe sahip düğümlerden oluşan bir ağ tipidir. Bu ağlar, araçlar ve yol yanı birimlerinden oluşurlar. İlgili ağdaki düğümlerin herbirinde kısa mesafeler arası kablosuz iletişim kurmayı sağlayan araçlar mevcuttur. Bu ağlarda kullanılan araçlar kısa mesafeli kapsama alanı sağladıklarından, ağ topolojisi sık sık parçalanır. Yani, herhangi bir anda ağdaki bir araç hiçbir araçla iletişim kuramayacak bir durumda kalabilir. Araçlar arası ağlar genel anlamda karayolu trafiğindeki araçlar ve ek olarak özel yeteneklere sahip yol yanı birimlerinden oluşurlar.

Araçlar arası ağlar; sürücü güvenliği, araç trafiği kontrolü, genel amaçlı uygulama kullanımı gibi amaçlar güden geniş bir araştırma alanıdır. Bu işlerin gerçekleştirildiği yol tipinin karakteristiğine göre haberleşme yordamları da birbirlerinden ayrılırlar. Örneğin, şehir içi ulaşımda araç sayısı fazla, araç hızı azken, otoyollarda araç sayısı az araç hızı fazla, kırsal kesimdeki yollarda da araç sayısı az araç hızı da azdır. Bu çeşitlilikler topolojinin yapısında ve değişkenliğinde kayda değer seviyede farklılıklara yol açtığından ötürü, literatürde tasarımı yapılan algoritmalar da genellikle tek bir yol tipinde çalışmak üzere üretilirler.

Araçlar arası ağların özgün karakteristiği, bu ağları diğer türden kablosuz ağlardan ayırmaktadır. Bu yüzden, bu alana özgü bir çok problem doğmaktadır. Bu problemlerin büyük bir kısmı araçların hareket örüntülerinin içinde bulunulan ortama göre ciddi şekilde değişmesinden ve bu örüntülerin öngörülmesinin zorluğundan kaynaklanmaktadır.

Bir çok yönlendirme algoritması hem şehir içi yollarda hem de şehir dışı yollarda aynı anda yüksek başarım sağlayamamaktadır. Araçlar arası ağların bu yapısından ötürü, çok sekmeli iletişimler kurabilmek oldukça zor bir problemdir. Sıkça başvurulan yöntemlerin çoğu beklenen başarımı gösterememektedir. Çünkü, çok sekmeli iletişimlerde, araçların hareketliliği yüksek olduğundan iletişim sıklıkla kopmakta, hatta topolojide parçalanmalar olabilmektedir.

Çok sekmeli iletişimlerde, iletişim kanalının kapasitesinin yüksek oranda kullanımını sağlamayı amaçlayan yöntemler henüz yaygın değildir. Tez kapsamında tasarlanan modellerde iletişim kanalının yüksek oranda kullanımının sağlanması amaçlandı. Elde edilen başarılı sonuçlara ulaşırken, literatürdeki çoğu yöntemin aksine hücresel ağları, aynı anda ortamda bulunabilen iletişimleri, yönlendirilebilir antenleri ve buna benzer maliyet getiren cihazların kullanılmasından kaçınıldı.

Bu tezde, kümelenmiş araçlar arası ağlarda araç - araç - ünite tipi iletişimlerin zamanlamasını yapabilen yöntemler tasarladık. Amacımız, iletişim kanalının yüksek oranda kullanımını sağlamaktır. Bu amaçla, araç kümesinden üniteye yükleme

ve üniteden araç kümesine indirme olmak üzere iki zamanlama modeli tasarladık. Tasarladığımız yöntemlerde her bir aracın kendine has veri alış-verişleri olduğunu, aynı verinin alış-verişinin birden fazla araç için yapılmadığı durumu ele aldık. Araç - ünite tipi iletişimlere ek olarak gerçekleşmesini sağladığımız araç - araç - ünite tipi iletişimler sayesinde iletişim kanalının etkin kullanımını sağladık.

Araç - araç - ünite tipi iletişimlerin başarıyla gerçekleşmesini sağlamak için sakla ve ilet tipi iletişim kavramından yararlandık. Sakla ve ilet tipi iletişimlerde, ara bağlantı düğümü alıcı ve vericiyle o an için iletişim kuramıyor olsa bile, elindeki mesajı ilgili hedefe gönderene kadar saklar. Bu yöntem gecikmeye toleranslı ağlarda sıkça kullanılsa da, araçlar arası ağlarda kullanılabilmesi için ek işler gerekir. Bu tez içerisinde, araçların sınırlı ve öngörülebilir bir hareketlilik örüntüsüne sahip olmasından faydalanarak sakla ve ilet tipi iletişimleri kullandık.

Tezdeki yöntemler, araçların bir küme halinde ilerlediği durum için tasarlanmışlardır. Aynı kümedeki araçlar, aynı yönde hareket eden ve birbirine yakın hızlara sahip olan araçlardır. Her bir kümenin bir küme lideri vardır. Küme lideri, küme içi organizasyonu sağlayan sıradan bir araçtır.

Küme liderinin kontrolü altında, ünitenin kapsama alanı içerisindeyken boş zamana sahip olan araçlar, veri transferini tamamlayamayacak durumda olan araçlara gönüllü olarak yardım ederler. Bahsedilen yöntemde araç - ünite tipi iletişimlere ek olarak kullanılacak olan araç - araç - ünite tipi iletişimler, doğrusal programlama yönteminin yardımıyla belirlenir. Hangi aracın hangi araç için ne kadar süreliğine ve hangi andan itibaren gönüllü olacağı probleminin doğrusal programlama problemine dönüşümü, tezin içeriğini oluşturmaktadır. Tasarlanan yöntem küme tabanlı olduğu için, ölçeklenebilirliği yüksektir.

Tezde tasarımı yapılan yöntemde, küme lideri araçların ivmelerini, hızlarını ve pozisyonlarını anlık olarak bilmektedir. Bu bilginin elde edilmesi için bir çok yöntem kullanılabilir. Küme lideri, henüz yol yanı ünitesinin kapsama alanına girmeden önce, araçların yol yanı ünitesine yükleyeceği veri miktarını bilmektedir. Küme lideri, kümedeki araçların indireceği veri miktarını ise, herhangi bir küme üyesi yol yanı ünitesinin kapsama alanına girdiğinde öğrenir. Bu bilgi sayesinde küme lideri; her bir aracın yol yanı ünitesinin kapsama alanına giriş ve çıkış anlarını, her bir aracın kümedeki bir diğer aracın kapsama alanına ne zaman girip çıktığını bilir. Özetle, küme lideri topolojideki her bir değişikliğin ne zaman ve nerede yaşanacağını bilir.

Küme lideri topolojideki her bir değişikliğin bilgisini elde etmesi sayesinde, topolojinin değişmediği en küçük zaman aralıklarını tespit eder. Bu zaman aralıklarında da kümedeki araçlardan hangilerinin birbirleriyle görüşebildiklerini tespit eder. Küme lideri halihazırda hangi aracın ne kadar bir veri transferi yapacağını ve bu transferin hangi yönde gerçekleşeceğini de bilmektedir. Bu sayede, doğrusal programlama yöntemlerini kullanarak; topolojinin değişmediği her bir anda hangi araç ikilisine iletişim verileceği veya hangi aracın yol yanı ünitesi ile iletişime geçebileceği tespit edilir. Topolojinin değişmediği en küçük zaman aralığı birden çok iletişim tarafından zaman paylaşımlı olarak kullanılabilir. Bu durumdan kaynaklı olarak, modelin son adımında topolojinin değişmediği en küçük zaman aralığının içinde bir zamanlama daha yapılır. Tüm bu işlemlerin ardından hangi aracın hangi anda hangi araçla(veya yol yanı ünitesi ile) iletişime geçeceği bilgisi elde edilir. Küme lideri, tasarlanan modeli çalıştırarak elde ettiği sonucu kümedeki tüm araçlara ve yol yanı ünitesine dağıtır. Yol yanı ünitesi ve kümenin diğer elemanları küme liderinin direktiflerine uygun hareket ederek veri transferlerini gerçekleştirirler.

Tasarlanan yordam, Java dilinde geliştirilen benzetim yazılımları yardımıyla test edilmiştir. Elde edilen sonuçlara göre; tasarlanan algoritma ilk biten öncelikli ve ilk giren öncelikli şeklinde çalışan zamanlama algoritmalarından açıkça üstün sonuçlar üretmektedir. Ek olarak, tasarlanan yöntem uç test durumları ile denenmiştir. Bu durumların hemen hepsinde diğer algoritmalardan çok daha iyi sonuçlar elde edilmiştir. Bunun yanında, gerçekçi senaryolarda elde edilen sonuçlar, tasarımın iletişim kanalını neredeyse tamamen kullanabildiğini göstermiştir.

1. INTRODUCTION

Vehicular networks are comprise of vehicles and stationary units that are equipped with short range wireless communication devices. Vehicular networks are promising research area which is expected to increase driver safety, control vehicular traffic better, enable wider use of infotainment applications and beyond [2]. Nature of the vehicular networks diversifies itself from other kind of wireless networks, creating a whole new research area.

1.1 Definition of Problem

Vehicular networks has unique characteristics when it compared to other kind of wireless ad-hoc networks. Mobility of the nodes in vehicular networks are significantly higher which causes frequent partitions on the network topology [3]. In a frequently partitioned network, multi-hop communications are not viable due to loss of existing communication links. Hence, utilization of communication channel can drastically decrease. However, since the vehicles mobility are limited with roads, pattern of their mobility is predictable. Estimating future topology changes based on predictable mobility, can lead a scheduling scheme for multi-hop communications.

1.2 Purpose of Thesis

Our motivation is increasing utilization of communication channel by proposing an efficient and scalable scheduling model for vehicle to infrastructure (V2R) and vehicle to vehicle to infrastructure (V2V2R) communications. Proposed methods can be implemented without a need for accessing other mobile network services e.g. cellular networks or without a need for performance enhancing tools such as directional antennas or multiple antennas. In the proposed model, vehicles constitute clusters. Each cluster determines its scheduling for V2R and V2V2R respectively. Proposed methods are aimed to be scalable with aid of clusters. In order to maximize the utilization, designed model adapts and combines some well known optimization techniques with a novel approach. All designed algorithms have polynomial time complexity.

1.3 Contributions of Thesis

Contributions of the thesis are:

• Demonstrating that use of clusters achieve higher utilization ratio with a scalable fashion

• Demonstrating that without an efficient scheduling model, communication channel is utilized inefficiently.

• Designing an efficient scheduling model that is close to fully utilizing communication channel.

• Designing a two step scheduling model for uplink utilization of V2V2R and V2R, which comprises of a task scheduling algorithm and a linear programming problem.

• Experimentally observing the best known task scheduling algorithm for first step of uplink utilization model.

• Designing a scheduling model for downlink utilization of V2V2R and V2R which turns scheduling problem into a linear programming problem.

• Comparing proposed scheduling models with existent scheduling algorithms in different scenarios.

1.4 Structure of Thesis

This thesis is organized as follows: Literature survey that mentions vehicular networks and current research on communication channel utilization, are given in the next chapter. Chapter 3 introduces proposed models for uplink and downlink utilization in clustered vehicular networks. Comparative simulation results of proposed models and existing algorithms are presented in Chapter 4. Finally, section 5 concludes the thesis and giving future works.

2. LITERATURE SURVEY AND MOTIVATION

In this chapter, vehicular networks briefly summarized. Current status of the research that is close to our work is presented. Methods that are being used have briefly presented.

2.1 Vehicular Networks

Vehicular ad hoc networks (VANET), has taken considerable attention recently due to emergence of Intelligent Transport Systems (ITS). ITS aims to enable use of a vast range of applications e.g. improved driver safety, infotainment applications and traffic efficiency [4].

IEEE 1609 [1] proposed a protocol stack to be used in vehicular environments(Fig. 2.1). However, it has been pointed out that applications with different kind of requirements might need extensions to this stack [5].

In [6], authors analysed broadcasting in IEEE 1609. Authors pointed out that IEEE 1609 can cause severe packet loss due to collisions.

ITS applications usually require stationary infrastructures near the roads that can communicate with vehicles [2]. Infrastructures are also addressed as roadside units (RSUs). The use of RSUs provides improved driver safety, better quality of service, helping to improve the performance of the network. It is unreliable to design VANET by introducing only ad-hoc communication features without a fixed infrastructure. In ITS, both V2V and V2R communications are enabled. Moreover, concurrent use of V2V and V2R communications are vital to improve performance of network and fulfilling requirements of ITS applications.

Additionally, use of RSUs are vital to ensure security of the vehicular network, since there might be extensive range of attacks to network due its partitioned nature. RSUs are trustworthy nodes of the network for vehicular nodes [7]. In vehicular networks, placement of RSUs is a challenging problem. For highway and rural areas, some

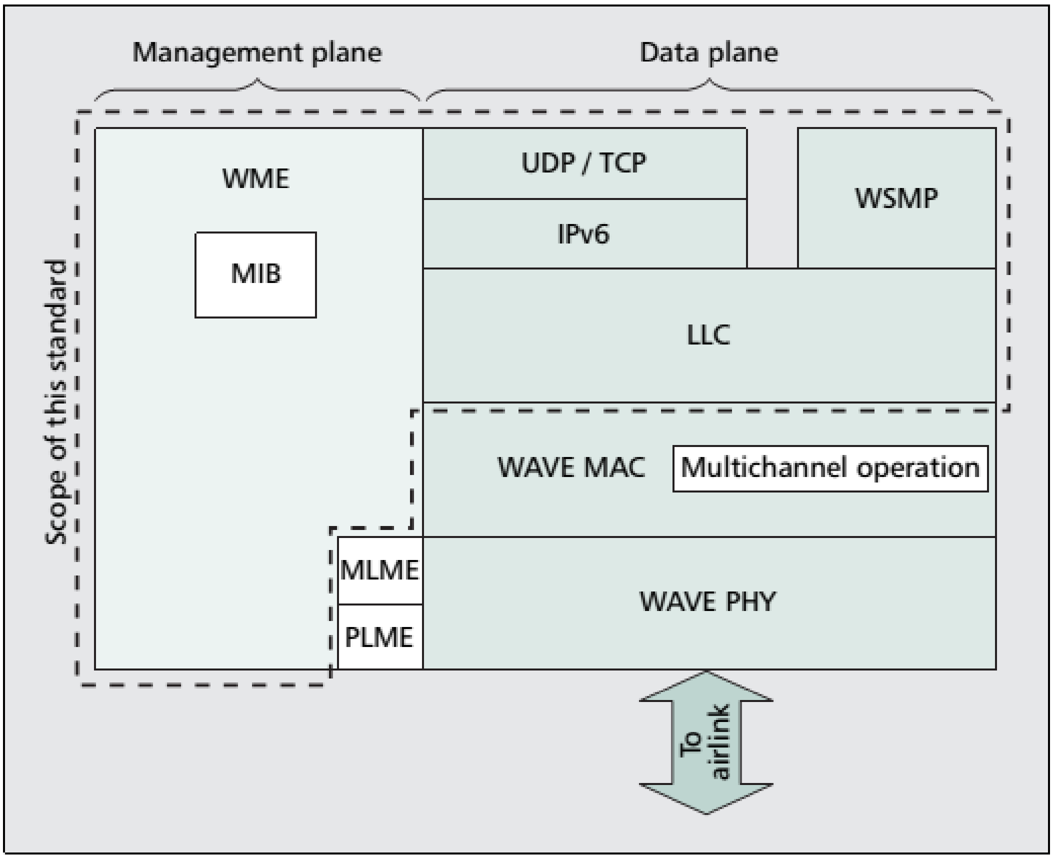


Figure 2.1: IEEE 1609 protocol stack [1].

probabilistic straightforward approaches are available [8]. But in the urban areas, placement of RSUs still stays as an open problem due to highly diverse mobility patterns of the vehicles. Most of the applications explicitly assume that RSUs are deployed to cross-roadings and traffic lights in urban areas.

Mobility patterns of the vehicles are required to be estimated to have an efficient communication and routing model. In the literature, mobility patterns are divided to parts as: macro mobility, which is interested in checkpoints of the vehicles and micro mobility, which considers rather short ranged models [9]. Macro mobility models are still far away from being stable which makes multi-hop routing quite challenging [3].

Most of the time, clustering mechanisms in vehicular networks, relies on mobility patterns. In [10], authors propose an approach that seems more stable than other approaches. However, the mobility patterns they have used is not quite realistic.

Traffic information is vital to create efficient routing algorithms in vehicular networks. Congestions in vehicular traffic conditions requires different approaches for routing mechanisms. In [11] and [12], authors tried to achieve better performance by making use of traffic information. However, their routing scheme creates huge overhead of packets which drastically degrades performance. In [13], authors used an adaptive beaconing method to overcome bandwidth waste. But they did not explicitly state how did they obtained traffic information which can be expensive in terms of use of system resources.

Beaconing is widely used in vehicular networks in order to keep other nodes informed for the network. In [14] authors pointed out that processing beacons might spend significant computational resources for a vehicle. In their approach, they have evaluated relevance of a beacon with the sender vehicles properties. Their method is a computationally light-weighted heuristic algorithm.

In [15], authors investigated connectivity probability of V2V2R and V2R communications. They assume fixed point RSUs which enable any vehicle to reach any RSU in 2 hops. Also, instead of a vehicular traffic pattern, they have used poisson distribution. This could be unrealistic in a city scenario since inside of the cities due to traffic lights, vehicles are not able to protect their poisson property. They have tested their analytical results for unit disk model and log-normal shadowing model.

Data dissemination is an important and challenging aspect of vehicular networks for ITS applications. In [16], information dissemination is performed with we use dynamically generated backbone vehicles. In order to select backbone vehicles, they used movement patterns and link quality. Link quality of neighbour vehicles is calculated with a fuzzy logic approach. They have not address time complexity of their protocol which could be considerable. However, their simulation results have shown significant improvement. In [17], authors proposed an elegant method that adapts itself to scale of the network. They have targeted compatibility with possible ITS applications where most of the researches lack of. Their model significantly outperforms other routing algorithms in terms of delay and throughput.

In vehicular networks, multichannel medium access is vital to improve performance. However, it is rather difficult to accomplish in a large-scale vehicular network. [18] proposes an asynchronous multichannel MAC scheme for large-scale vehicular ad hoc networks. Their purpose is reducing collision rate on control channel and load balancing between service channels. They have used a distributed time division multiple access. Simulation results demonstrates that their work outperforms IEEE 1609 protocol.

Recently, cloud computing is started to be investigated in vehicular environments. In [19], authors described a taxonomy for cloud computing in vehicular environments and pointed out the possible challenges ahead. They have stated that there are three kind of major architectures which are vehicular clouds, VANET using the cloud and a hybrid model. However, they only provide a high level view which lacks of details of the each architecture. [20], presents a cloud service discovery protocol in vehicular environments. Described architecture offers collaborative use of vehicles' individual resources such as access to cellular networks and storage space. They use RSUs as cloud directories in their architecture which is tested in an urban scenario. Despite high density of the RSUs in their tests, obtained results are not satisfactory. It could have been caused by the routing algorithm they have used.

Cooperative behaviour of vehicles can significantly improve network performance and it may even allow video transmission. In [21], authors proposed a video downloading method in a clustered vehicular network. In their work once a member of the cluster demands a video, other members use their cellular network capabilities and download some parts of the video for the demanding vehicle. By using short range communications, demanding vehicle collects all parts of the video. However, simulations show that increasing number of helping vehicles did not improve the performance as expected. Since the routing inside of the cluster is not well managed, proposed method is distant from being efficient, even though it uses cellular network infrastructure.

Simulation is preferred over real-world test in vehicular networks due cost reasons. However, there are a lot of simulation environments none of which is considered as the most trustworthy. In VEINS [22], authors present a simulation environment for vehicular networks. VEINS uses SUMO [23], which is a realistic urban mobility generator. SUMO can be programmed in order to generate different traffic patterns. In VEINS, OMNeT++ [24] is used to simulate network, which is a widely known cross-platform general purpose network simulator. VEINS is a simulator which combines SUMO and OMNeT++ to allow simulation of vehicular networks.

2.2 V2V2R and R2V2V Communications

In [25], a resource allocation scheme of V2V and V2R communications is proposed. An interference graph is used where both V2V and V2R links are coexists. V2V2R is a hybrid of V2V and V2R communications where a vehicle is used for relaying purposes for communication between another vehicle and RSU. In [26], a resource allocation scheme in downlink for R2V2V is proposed. They used multiple smart antennas to improve share of resources. In [27], a V2V2R architecture is introduced. Architecture did not explicitly address resource sharing problem. In [28] and [29], a relatively similar problem is discussed from the cellular networks' perspective. Our work does not rely on smart antennas or cellular networks or coexistent links.

2.3 Scheduling

Scheduling of communications can be considered as a job scheduling problem. This section briefly presents scheduling techniques that have been used in this thesis.

2.3.1 First come first served

In first come first served (FCFS) technique, a job (communication) that arrives first uses all resources until it is finished. Other jobs are scheduled by their order of arrival time to system. This is a nonpreemptive technique.

2.3.2 Earliest deadline first

In earliest deadline first (EDF) technique [30], system always selects to run the job (communications) which is closest to its deadline. It is an optimal and preemptive scheduling algorithm.

2.3.3 Linear programming

Linear programming is a technique for defining maximum output of a linear function in which its variables are constrained by linear relationships. There are a lot of methods in the literature for solving a linear programming problem [31]. Linear programming can also be used for solving scheduling problems.

2.4 Motivation

In order to achieve higher utilization in the transmission media, a resource sharing policy is required. Using only V2R communications does not solve the scheduling problem since each vehicle might have different amount of demanding data or velocity. Moreover, V2V communications can be available only for short time intervals due to high mobility of the vehicles. In an ad-hoc or opportunistic manner, benefits of V2V communications might not be exposed. Aiming a better utilization requires efficient use of V2V communications which can be enabled by an efficient scheduling model.

3. UPLINK AND DOWNLINK UTILIZATIONS

Our work is presented in two parts. First part presents scheduling of uplink utilization [32] while second part presents scheduling of downlink utilization [33]. Both scheduling models designed to work under same assumptions and in same environment.

Proposed model is executed by cluster head. Primary reason of using clusters is to obtain a scalable method. Model might have been executed by RSU, but it could excess the computing resources of the RSU. Even with a polynomial time algorithm, RSU can be overwhelmed in a traffic jam scenario. However when the cluster heads intervene, algorithm could be scalable since each cluster head handles scheduling of a limited number of vehicles. In this sense, RSU has no responsibility on scheduling of data transfers for each vehicle. After the execution of the algorithm, cluster head broadcasts scheduling directions to cluster members.

3.1 Assumptions

Considered vehicular network scenario comprises of a RSU and a cluster of vehicles. Each member of the cluster has its own downloading demands from RSU. Under the assumption that vehicles move in forms of clusters, every cluster has a cluster head. Moreover, clusters are not allowed to accept any new members to the cluster during the transmission process. Additionally, every member is assumed to be moving with the cluster along the transmission process.

Having more than one clusters within the range of RSU is not scope of this work. However, different clusters might work in different transmission channels or they might negotiate about usage of the current channel(s). Cluster head has following data about each vehicle in its cluster: Position, initial velocity and average acceleration. In order to keep the model simple, an ideal and error-free transmission environment is assummed for the transmission of payload.

RSUs are usually planned to deploy at corner of the road crossings where clusters of vehicles have tendency to be split up or accept new vehicles to the cluster. Therefore, proposed scheduling model assumes the worst case possibility and does not perform any scheduling decision for a vehicle that left RSU coverage.

3.2 Uplink Utilization

Model comprises of two steps. First step can be either earliest deadline based or first come first served based scheduling which will be employed for direct V2R communications. Second step is to find a schedule for additional V2V2R communications if possible and required.

Step 1: Scheduling V2R communications

Consider an algorithm that aims increasing total amount of data to be uploaded by a cluster, without making use of V2V2R communications. One of the most feasible approaches would be using an optimal task scheduling algorithm such as earliest deadline based scheduling [30]. Task scheduling requires knowledge of following three properties for each task: Arrival time, transmission time and deadline. Arrival time of a vehicle is its entrance time to RSU coverage. Deadline of a vehicle is its leaving time of the RSU coverage. Transmission time of the vehicle is its transmission delay during upload of the data.

In order to achieve maximum utilization for V2R communications, earliest deadline based scheduling is used with a slight modification. Vehicles that are unable to upload their entire data will be suspended. Thus, when a vehicle leaves RSU coverage, it is not able to upload data. In this step, each of the direct V2R communications is defined.

Performance of such an algorithm strictly depends on properties of vehicles. It is very likely to observe a scenario where some vehicles are unable to complete uploading their data whereas some other vehicles have idle time in the RSU coverage. Idle time interval is described as an interval where any vehicle inside the RSU coverage does not have data to upload.

In the next step, vehicles that are unable transmit their data completely, will migrate their remaining data to the vehicles which have idle time in the RSU coverage.

Step 2: Scheduling V2V2R communications

This step of the model aims to increase total amount of data to be uploaded by making use of V2V2R communications. Conceptually, V2V2R communications can be performed in two different ways.

First way: Migration section (V2V) of the communication is performed in an idle time interval. Thus, V2V2R communication will require another idle time interval for V2R section. This yields that first method spends twice idle time intervals for a communication.

Second way: Migration section (V2V) of the communication is concurrent with an EDF scheduled V2R communication. This method utilizes system resources better than the first one, since the migration of the data does not spend idle time interval for V2V communications.

Designed model uses both of these ways to make the best scheduling decision.

Firstly, senders and relays of the possible V2V2R communications are defined. Based on first step of the model, a vehicle is sender if it has remaining data i.e. it was not able to upload all its data before leaving time of RSU coverage. A vehicle is relay for the possible V2V2R communications if it has idle time interval i.e. vehicle has uploaded its data completely and while it was inside of the RSU coverage, there is a time interval where any of the vehicles do not upload data to RSU.

Subsequently, migration time intervals for each sender and relay pairs are defined. Migration time interval is a time interval where the distance between communicating vehicles is smaller than communication range and there are not any colliding direct V2R communication from Step 1 during this time interval. Moreover, establishment time of migration time interval cannot be later than sender's entrance time to RSU coverage. If relaying vehicle is inside of the RSU coverage during the migration interval, this is a first way of V2V communication. If the termination of migration time interval is earlier than relay's entrance time to RSU coverage, it is a second way of V2V communication. Another possibility is, relay's entrance time to RSU coverage is inside migration interval. This implies that migration time interval has successive first and second way of communications.

Defined migration intervals can still collide with each other since a migration interval can be used by any V2V communication. Note that a migration time interval is defined by three properties: Sender, relay and a time interval for communication between sender and relay. In order to prevent collision of different pairs of V2V communications, proposed model allows only one V2V communication for any time interval. On the other hand, a V2V communication and a direct V2R communication from Step 1 can be concurrent.

Moreover, migration intervals must be separated from each other. This yields that, it is necessary to define the smallest time intervals where the network topology does not change. A topology change is creation of a new communication link or removal of a current communication link. Note that RSU is a node of this vehicular network. Thus, a change of V2V2R way for any V2V link is also a topology change. Migration time intervals and idle time intervals are divided so that no topology change occurs during these intervals. The reason behind dividing idle intervals is that concurrent V2V2R communications are not allowed. Since an idle interval can be used for a way of first V2V2R communication, it can also be a part of any migration interval.

Definition of smallest time intervals allows globally addressing any time interval since all of them are atomic. After dividing migration and idle time intervals, proposed model generates all possible V2V2R communications. This is a straightforward programming problem. Each migration time interval is paired with an idle time interval of its relay. Since this is an upload process, migration time interval takes place before the idle interval. This means that in a V2V2R communication, V2V happens before V2R. Another possibility is migration and idle time intervals use the same time interval. Such a scenario implies shared use of the time interval which yields that only half of interval's capacity can be used to upload data. Because, both V2V and V2R will spend same amount of time in the interval.

V2V2R communications is presented in $V_S T_X V_R T_Y R$ format, where;

- V_S is sender vehicle.
- T_X is migration interval, used for V2V of V2V2R.
- V_R is relaying vehicle.
- T_Y is idle time interval, used for V2R of V2V2R.
- R is RSU.

Besides, a T_X interval might be used by any V2V2R communication. Each V2V2R communication that uses T_X, must share T_X interval. Same rule also applies to T_Y interval.

Another issue that requires attention is $V_S T_X V_R T_X R$ communications. Note that T_X is used by both V2V and V2R. This kind of communications spend twice amount of time from T_X. If the V2V2R communication is allowed to use entire T_X, first half of T_X will be used for V2V link, second half of T_X will be used for V2R link. This implies that capacity limit of $V_S T_X V_R T_Y R$ type communication is $T_X/2$.

Furthermore, V_S has limited data for uploading. V_S does not need to have more V2V2R communications than its remaining data. Thus, any V2V2R communication that has V_S as sender, must share the V_S's remaining data.

Constraints mentioned above can be presented in the linear programming as follows:

Variables of the problem are amount of time used by each V2V2R communication. Note that amount of time used by V2V part of the communication is equal to the amount of time used by V2R part of the communication. This approach allows avoiding equality equations in order to decrease complexity of the solution.

Amount of time used by each V2V2R communication is named as Z_i. Number of Z_i variables is n. Variables are not allowed to be smaller than zero.

For each T_j, where T_j is a migration or idle interval,

$$T_j \geq \sum_{i=1}^{n} f(Z_i, T_j) \tag{3.1}$$

$$f(Z_i, T_j) = \begin{cases} 0, & if\ \ T_j\ \ is\ \ not\ \ used\ \ in\ \ Z_i \\ Z_i, & if\ \ T_j\ \ is\ \ used\ \ in\ \ Z_i\ \ once \\ 2Z_i, & if\ \ T_j\ \ is\ \ used\ \ in\ \ Z_i\ \ twice \end{cases} \tag{3.2}$$

In (3.2), requirements of $V_S T_X V_R T_X R$ is satisfied with the last case of the function. If T_X is used by $V_S T_X V_R T_X R$, maximum amount of time used by communication will be $T_X/2$, since $T_X \geq 2Z_i$. However, entire interval of T_X will be spent despite $V_S T_X V_R T_X R$ only benefits half of T_X.

For each D_S, where D_S is amount of required time to upload remaining data of V_S:

$$D_S \geq \sum_{i=1}^{n} g(Z_i, V_S) \tag{3.3}$$

$$g(Z_i, V_S) = \begin{cases} 0, & V_S \ is \ not \ sender \ of \ Z_i \\ Z_i, & V_S \ is \ sender \ of \ Z_i \end{cases} \tag{3.4}$$

Objective of this linear programming is maximizing total amount of communication time. Each variable of this problem indicates amount of communication time for its $V_S T_X V_R T_X R$ or $V_S T_X V_R T_Y R$.

$$Maximize : \sum_{i=1}^{n} Z_i \tag{3.5}$$

Although this linear program can be solved with any appropriate algorithm, simplex method is preferred due to its simplicity.

Subsequently, when this linear programming problem is solved, value of each variable indicates how much time spent on a particular $V_S T_X V_R T_X R$ or $V_S T_X V_R T_Y R$ communication.

Moreover, there might be more than one communications sharing same T_X or T_Y. Last part of the model is defining intra-scheduling for T_X or T_Y intervals. V2V part must be guaranteed to be performed before V2R part for each individual V2V2R communication. It is already known that in a $V_S T_X V_R T_Y R$ communication T_X is before T_Y, which implies that they do not require an effort. In a $V_S T_X V_R T_X R$ communication, this can be easily achieved by allocating slots for V2V part of the communications before V2R parts. Note that this model did not address decreasing number of time slot usage switches; it only makes sure that V2V happens before V2R.

Finally, cluster head obtains V2V2R scheduling for each vehicle.

3.3 Downlink Utilization

Cluster head executes the proposed model right after entrance of first member to RSU coverage. In order to perform scheduling of a cluster, cluster head needs to know total amount of data to be downloaded by each member in its cluster. Thus, cluster head must obtain this data from RSU. In Fig. 3.1, message flow of this data is explained. Cluster gateway (CGW) is a cluster member which is the nearest vehicle to RSU coverage. CGW is relay between RSU and cluster head (CH) during transmission of size of the data to be downloaded by each vehicle. CH runs proposed model to obtain scheduling of downlink communications after it receives the data from RSU. Then CH distributes the scheduling to every member of cluster. CGW relays the scheduling to RSU.

R2V2V communications can be performed in two different ways. In the first way, relaying vehicle immediately transmits the downloaded data from RSU to receiving vehicle. However in the second way, relaying vehicle downloads receiver's data from RSU while relay and receiver are unable to communicate. Relay transmits downloaded data to the receiver after establishment of communication with receiver. Second way of R2V2V communications is a form of Store and Forward Mechanism [34]; relaying vehicle can store the downloaded message and is able to transmit it to the receiver in a later time. Direct R2V communications can be performed only while receiving vehicle is inside of the RSU coverage.

First step of the model is defining each vehicle's entrance and leaving time of RSU coverage. Vehicles can perform direct R2V communications and R2V part of the R2V2V communications while they are able to communicate with RSU. Moreover, creation and removal times of communication links between each pair of vehicles are defined. A V2V communication link is said to be created if the following conditions are met:

- Relaying vehicle is inside of the RSU coverage.
- Receiving vehicle did not enter the RSU coverage yet.
- Receiver is inside of the communication range of relay.

In Fig. 3.2, a legal communication is shown. After creation of communication link, if any of the mentioned conditions are violated, communication link is meant to be broken. V2V part of an R2V2V communication can be performed only while there is a link between relay and receiver. Proposed model does not allow multiple communications in any time interval since they are guaranteed to be collided. In this work, only two hops of relaying communications are considered. Algorithm 1

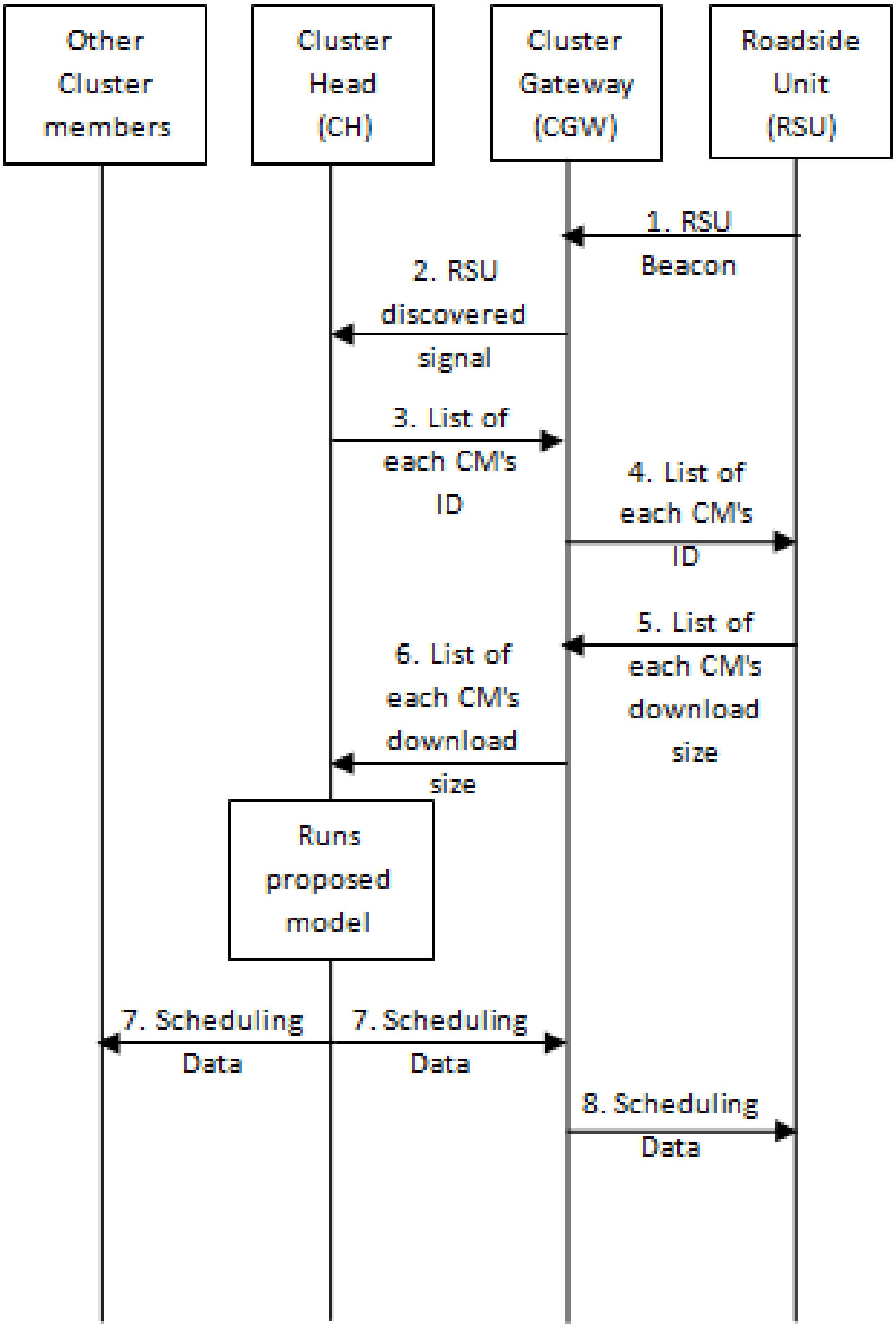


Figure 3.1: Message flow of the downlink model.

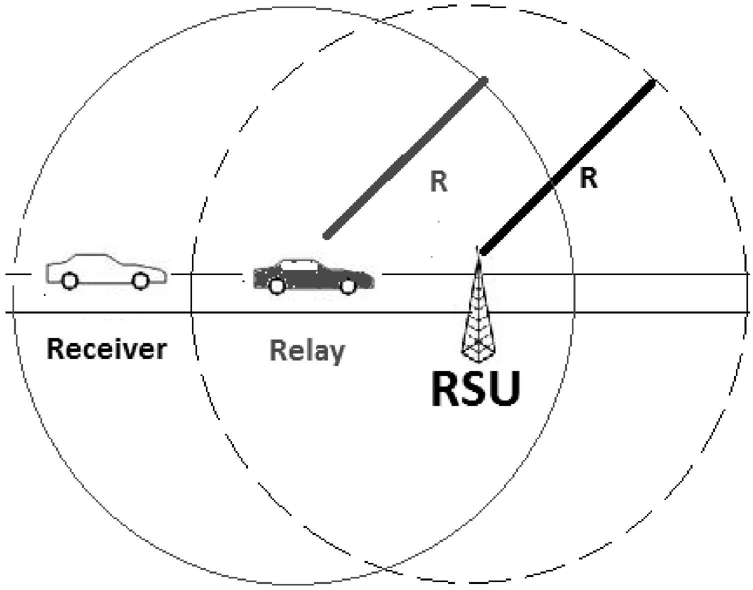


Figure 3.2: A legal V2V communication between relay and receiver.

is used for obtaining all possible first way of R2V2V communications. Algorithm 2 is performed after Algorithm 1, for obtaining all possible second way of R2V2V communications

In the proposed model, cluster head stores each possible V2V communication interval between all possible vehicle pairs in the cluster. It also stores all possible direct R2V communication intervals. This step ensures that cluster head has knowledge of all topology change times in this network since a topology change is creation or removal of any link.

Proposed model makes scheduling decisions where the network topology does not change. This approach allows the model to globally address each smallest time interval. Therefore, since the cluster head has the knowledge of each topology change time, it can divide any V2V or R2V communication interval based on topology change times. Moreover, relaying and receiving time intervals of the possible R2V2V communications are defined. In the first way of R2V2V communications, R2V and V2V parts of the communication is performed in the same time interval. This infers that half of the time interval can be used for downloading process since each of R2V and V2V will spend same amount of time in the interval for a R2V2V communication. In the second way of R2V2V communications, R2V part of the communication is performed while the relaying vehicle is inside of the RSU coverage and there is not a connection between relaying and receiving vehicles.

Algorithm 1: First way of R2V2V communications

```
1:  for each vehicle v in cluster
2:      define entrance and leaving time of v to RSU coverage
        //i.e. direct R2V communication interval.
3:      store to CommunicationsList
4:  end for
5:  for each vehicle pair v1 and v2 in cluster
6:      define establishment time of communication
7:      define termination time of communication
8:      store to CommunicationsList
9:  end for
10: store time of all topology changes to TCT array
    //i.e. values in 2nd, 6th and 7th lines.
11: sort and eliminate duplicates in TCT
    //TCT has all the topology change times.
    //a t_k interval is between TCT[k] and TCT[k+1].
12: for each communication in CommunicationsList
13:     for each element e in TCT
14:         if establishment < e < termination
15:             partite communication interval
                //turns to (establishment,e) and (e,termination)
16:             reorganize CommunicationList
17:         end if
18:     end for
19: end for
20: for each R2V communication in CommunicationList
21:     define global time interval ID based on TCT
22: end for
23: for each R2V2V communication in CommunicationList
24:     define R2Vand V2V global time interval IDs based on TCT
25: end for
26: //call Second way of R2V2V communications algorithm
```

Algorithm 2: Second way of R2V2V communications

```
1:  for each vehicle pair v1 and v2 in cluster
2:      if there is a time interval t_X that
            v1 and v2 cannot communicate
            and only one of them is inside RSU coverage
3:          for each first way of R2V2V communication λ
                between v1 and v2
4:              if t_X takes place before λ
5:                  create new communications where
                    V2V interval is same as time interval of λ
                    R2V interval is t_X
6:                  partite t_X of this communication based on TCT
7:                  store all to CommunicationList
8:              end if
9:          end for
10:     end if
11: end for
```

Please note that second way of R2V2V communications is expected to be scarce since its constraints are unlikely to be frequent in a highly mobile environment

A R2V communication should be presented in 3 char format defining the operation: $RT_A V_C$;

• R is RSU.

• T_A is the time interval for R2V communication.

• V_C is receiver vehicle

A first way of R2V2V communication should be presented in 5 character format defining the operation: $RT_A V_R T_A V_C$;

• R is RSU.

• T_A is the time interval for R2V2V communication. Both R2V and V2V are performed in this interval.

• V_R is relaying vehicle.

• V_C is receiver vehicle.

A second way of R2V2V communication should be presented in 5 character format defining the operation: $RT_A V_R T_B V_C$;

• R is RSU.

• T_A is the time interval for R2V.

• V_R is relaying vehicle.

• T_B is the time interval for V2V.

• V_C is receiver vehicle.

A T_A or T_B interval might be used by any R2V2V communication. Each possible direct R2V or R2V2V communication that uses T_A, must share T_A interval. It also applies to T_B. Furthermore, for the first way of R2V2V communications T_A will be shared by both R2V and V2V parts of the communication. Maximum amount of time that the first way of R2V2V communication can use for download is $T_A/2$ when it spends entire T_A.

Besides, V_C has limited amount of data to be downloaded. Total assigned transmission amount provided for V_C shall not exceed V_C's total demand.

Amount of time used by each direct R2V or R2V2V communication are variables of linear programming problem. For each R2V2V, amount of time spent on R2V is equal to the amount of time spent on V2V part of the communication. Such an approach provides avoiding equality equations in the linear programming which reduces the complexity.

Amount of time used by each direct R2V or R2V2V communication is named as Z_i. Number of total variables is named as n. All variables are greater than zero.

For each T_j, where T_j is a time interval used by a direct R2V or used by any part of R2V2V

$$T_j \geq \sum_{i=1}^{n} f(Z_i, T_j) \tag{3.6}$$

$$f(Z_i, T_j) = \begin{cases} 0, & if\ \ T_j\ \ is\ \ not\ \ used\ \ in\ \ Z_i \\ Z_i, & if\ \ T_j\ \ is\ \ used\ \ in\ \ Z_i\ \ once \\ 2Z_i, & if\ \ T_j\ \ is\ \ used\ \ in\ \ Z_i\ \ twice \end{cases} \tag{3.7}$$

(3.7), satisfies requirements of first way of R2V2V by last case of the function. Z_i variable of $RT_AV_RT_AV_C$ is constrained by $T_A \geq 2Z_i$. Note that direct R2V communications are constrained by limits of one time interval while second way of R2V2V communications are constrained by limits of both T_A and T_B. Second way of R2V2V spends same amount of time from T_A and T_B.

For each D_C, where D_C is amount of required time to download demanding data of V_C:

$$D_c \geq \sum_{i=1}^{n} g(Z_i, V_C) \tag{3.8}$$

$$g(Z_i, V_c) = \begin{cases} 0, & V_c\ \ is\ \ not\ \ receiver\ \ of\ \ Z_i \\ Z_i, & V_c\ \ is\ \ receiver\ \ of\ \ Z_i \end{cases} \tag{3.9}$$

Objective of this linear programming problem is maximizing total amount of communication time. Each variable of this problem indicates amount of communication time for its R2V2V or direct R2V.

$$Maximize : \sum_{i=1}^{n} Z_i \qquad \textbf{(3.10)}$$

This linear program can be solved with any appropriate algorithm. Simplex is preferred for its wider use and availability to different platforms.

Furthermore, solution point of this linear programming problem indicates how much time spent on a particular R2V or R2V2V communication within each smallest time interval.

Subsequently, one time interval might be used by more than one communication. In the last step, proposed model defines intra-scheduling for smallest time intervals. For the first way of R2V2V communications, R2V part must be guaranteed to take place before V2V part for each individual R2V2V communication. For the second way of R2V2V, there is no need for an intra-scheduling since R2V part of the communication explicitly performed before V2V. Direct R2V communications do not require additional work for an intra-scheduling since they do not have successive communications.

4. SIMULATIONS AND RESULTS

This section presents simulation environment for the vehicular network scenario and comparison of proposed models with existing models.

4.1 Simulation Environment

A straight road with one lane is simulated. Every vehicle and RSU has a transmission range of 150 meters. Every cluster member travels in same direction with constant velocity. Distance between first and last vehicles in the cluster is 300 meters (Fig. 4.1). Cluster has 10 vehicles. Bandwidth of the channel is 4 Mbps. Velocities of vehicles vary between 11 - 18 m/sec (40-60 km/h).

Simulation is developed in Java for cross compatibility issues. Apache Commons Foundation's Math Library is used for implementation of simplex algorithm. Executable file of the simulation generates scheduling and visualizes it as in Fig. 4.3 and Fig. 4.5. (Readers can find the executable jar file at www.futurist.itu.edu.tr).

4.2 Uplink Simulation

In the simulation, scheduling begins right after any member of the cluster has entered RSU coverage. This is the worst case scenario of the model since direct V2R communications will interfere with V2V communications by colliding with them. This will decrease available time for V2V communications and create a significant disadvantage for proposed model.

A cluster can upload data to RSU as long as at least one member is inside of the RSU coverage. Performance criterion is defined as utilization of this time interval i.e. how much percentage of this time is spent on uploading data to RSU. Please note that V2V communications are not considered as gain since they are not uploading any data. Total amount of time spent on V2R part of the V2V2R communications is summed to evaluate model's exact gain.

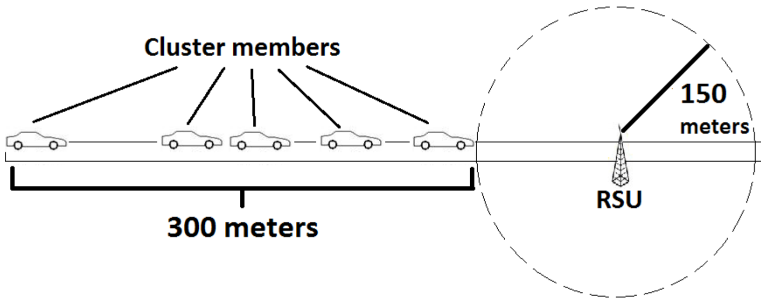


Figure 4.1: Visualization of simulation environment.

Following scheduling models have been compared:

- Earliest deadline first (EDF) only.
- First come first served (FCFS) only.
- Proposed V2V2R model, Step 1 uses EDF.
- Proposed V2V2R model, Step 1 uses FCFS.

In the scenarios, vertical axis indicates utilization while horizontal axis indicating increasing amounts of data the cluster has. Data is increased until the cluster is unable to send all its data.

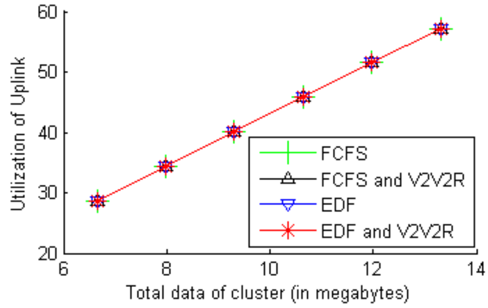
For scenario in Fig. 4.2(a), first vehicle of cluster has data to be upload, while others do not have data. In this scenario, V2V2R cannot be used since the vehicle has no available migration interval. Maximum utilization is 57.1% for each model.

For scenario in Fig. 4.2(b), vehicle that is in the middle of cluster has data to be upload, while others do not have data. Proposed model is able to achieve 63.6% utilization while others achieved 42.5%. V2V2R communications increased utilization up to 21%.

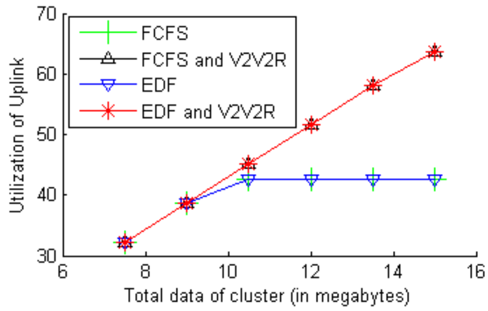
For scenario in Fig. 4.2(c), last vehicle of cluster has data to be upload, while others do not have data. Proposed model is able to achieve 71.2% utilization, while others still achieving 42.5% utilization. V2V2R communications increased utilization up to 28%. This is a better result than previous scenario since the sender vehicle has more migration intervals.

For scenario in Fig. 4.2(d), every vehicle of cluster has data to be upload with varying amounts. In this scenario, FCFS and EDF shown better results compared to previous scenarios. However, V2V2R communications are still able to improve utilization significantly. In the last test of scenario where some vehicles have remaining data on each models, following utilization ratios are obtained: FCFS achieved 81.5%, EDF achieved 85.8%, Proposed model where Step 1 is FCFS achieved 96.6%, Proposed model where Step 1 is EDF achieved 98.3% utilization. This scenario shows that proposed model can almost fully utilize uplink in a realistic scenario.

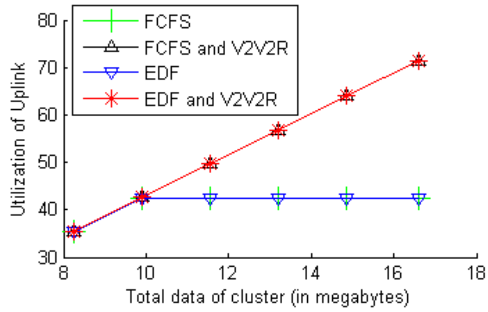
Fig. 4.3 shows scheduling of a sample run in Fig. 4.2(d) where 98.3% uplink utilization is achieved while using proposed model with EDF. Horizontal axis shows time in seconds. Vertical axis represents vehicles. Each vehicle has its individual color. Vertical straight and colored lines are entrance times to RSU coverage of each vehicle. Vertical dashed lines are leaving time of RSU coverage for a vehicle. Horizontal colored and thick lines are scheduling related lines. Horizontal bottom line shows communications where RSU is receiver. Single colored horizontal lines are direct V2R communications from Step 1. They have been generated by earliest deadline based scheduling. Lines which have gray lines inside them refer to a sender of a V2V communication. Outside of the line is painted with relay's color. Relay of V2V communication has black line in it. Outside of the line is painted with sender's color. V2R part of the communication has a black line in it, while outside is painted with relay's color. For fig. 4.3, there are three V2V2R communications. Two of them are between v10 and v8. Both of them are "way 2 of V2V2R" communications. V10 sent its data to v8 in (0, 2) and (3.56, 6,59). These two V2V communications are concurrent with other communications. V8 sent this data to RSU in (41.4, 43.4) and (43.4, 46.43) interval. Last communication is between V3 and V1. This is a "way 1 of V2V2R" communication. V3 sent its data in (2, 2.78) which is an idle interval, V1 sent this data to RSU in (2.78, 3.56) interval. Please note that there are not any uploading process to RSU in (2, 2.78) interval. In (0, 2) and (2.78, 46.43), there is always an uploading process.



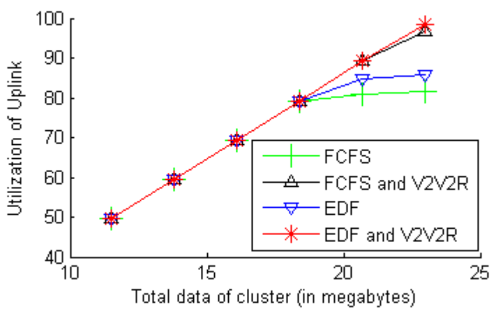
(a) First vehicle has all the data.



(b) Vehicle in the middle has all the data.



(c) Last vehicle has all the data.



(d) Every vehicle has varying amounts of data.

Figure 4.2: Uplink utilization results.

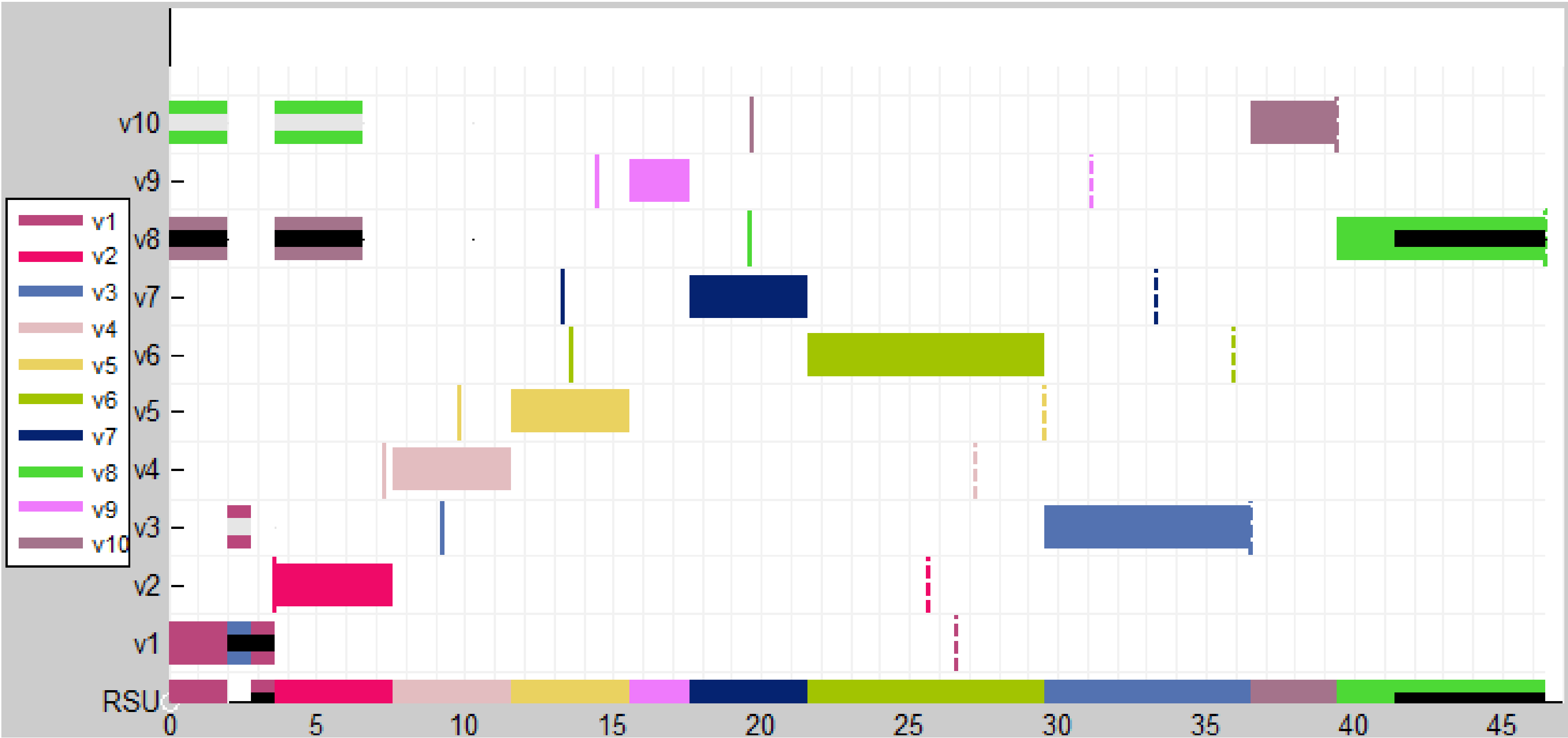


Figure 4.3: Scheduling of scenario in Fig. 4.2(d) where the proposed model achieved %98.3 utilization.

4.3 Downlink Simulation

A cluster can download data from RSU if any of the cluster members is inside of the RSU coverage. Utilization of total connection time with the RSU is defined as performance criteria i.e. cluster spent how much percentage of its connection time to the total download processes. Note that R2V2V communications are considered with only their V2V part of communication since R2V part is performed for relaying purposes and cannot be assumed as a download.

Following scheduling models have been compared with respect to utilization of downlink:

- Proposed model which allows both direct R2V and R2V2V.
- Earliest deadline first (EDF) which allows only direct R2V.
- First come first served (FCFS) which allows only direct R2V

In the figures related with the mentioned scenarios, utilization is represented in vertical axis. Horizontal axis represents increasing amounts of data the cluster needs to download. Total download demand of the cluster is increased until any member of the cluster is unable to receive all its data. Velocities of vehicles and their distance to RSU are fixed for all scenarios.

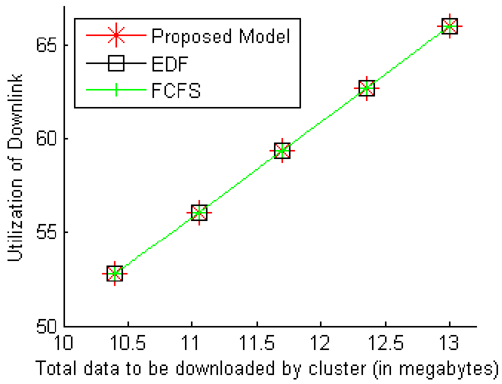
For scenario in Fig. 4.4(a), first vehicle i.e. nearest vehicle to RSU, has download demand while other vehicles do not have any data to be downloaded. First vehicle is unable to use R2V2V communications in this scenario since it cannot be receiver of any R2V2V communication. In this scenario, R2V2V cannot be used since the vehicle has no available V2V communication interval. Proposed model has achieved same utilization value with EDF and FCFS.

For scenario in Fig. 4.4(b), vehicle that is in the middle of cluster has download demand while other vehicles do not have any data to be downloaded. Proposed model utilizes downlink up to %10 better than the EDF and FCFS. Employment of R2V2V communications has provided this increase.

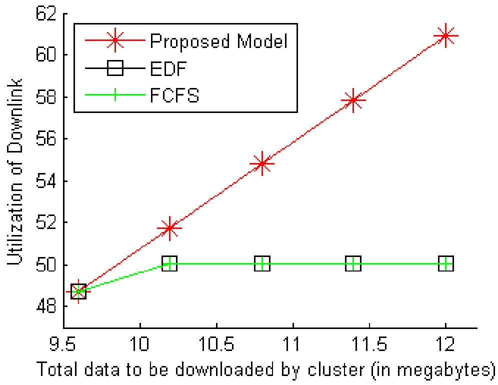
For scenario in Fig. 4.4(c), last vehicle of cluster has download demand while other vehicles do not have any data to be downloaded. Proposed model utilizes downlink up to %13 better than EDF and FCFS. Similiarly with the previous scenario, employment of R2V2V communications lead to better utilization.

For scenario in Fig. 4.4(d), every vehicle of cluster has varying amounts of data to be downloaded. In this scenario, FCFS and EDF has obtained better utilization compared to previous scenarios. However, proposed model has still significantly better utilization then FCFS and EDF. Proposed model utilizes downlink up to %6.5 better then the others.

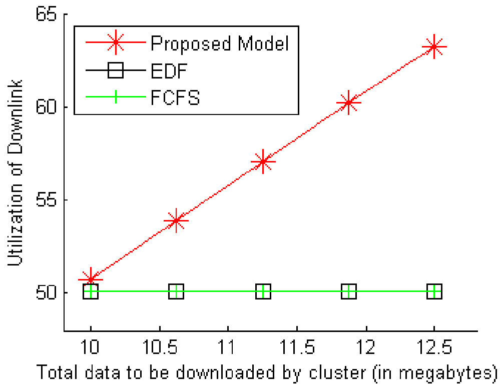
Fig. 4.5 presents scheduling of a sample run in Fig. 4.4(d) where %93.4 downlink utilization is achieved. Horizontal axis shows time in seconds. Vertical axis represents vehicles. Each vehicle's communication is represented in its horizontal space. Entrance time to RSU coverage for a vehicle is shown by vertical straight lines. Leaving time of RSU coverage for a vehicle is shown by vertical dashed lines. Horizontal thick lines are scheduling related lines. Horizontal bottom line shows downlink communications where RSU is sender. Single colored horizontal lines are direct R2V communications. Lines which have gray lines inside them refer to a receiver of a V2V communication. Relay of V2V communication has black line in it during R2V and V2V parts of the communication. For this sample, there are two R2V2V communications. Both of these R2V2V communications are between V1 and V2 where V1 is relay and V2 is receiver. Both of them are first way of R2V2V communications. V1 downloads V2's data in (2, 3.15) and relays it to V2 in (3.15, 4,3). After that, V1 downloads V2's data again in (4.31, 5.77) and relays it to V1 in (5.77, 7.23). Rest of the communications is direct R2V communications between vehicles and RSU. Note that communication media is always used during cluster's interaction with the RSU.



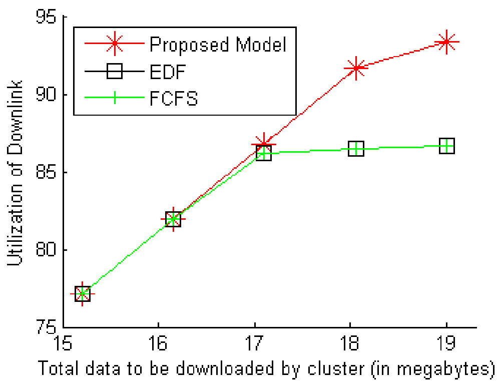
(a) First vehicle has all the data.



(b) Vehicle in the middle has all the data.



(c) Last vehicle has all the data.



(d) Every vehicle has varying amounts of data.

Figure 4.4: Downlink utilization results.

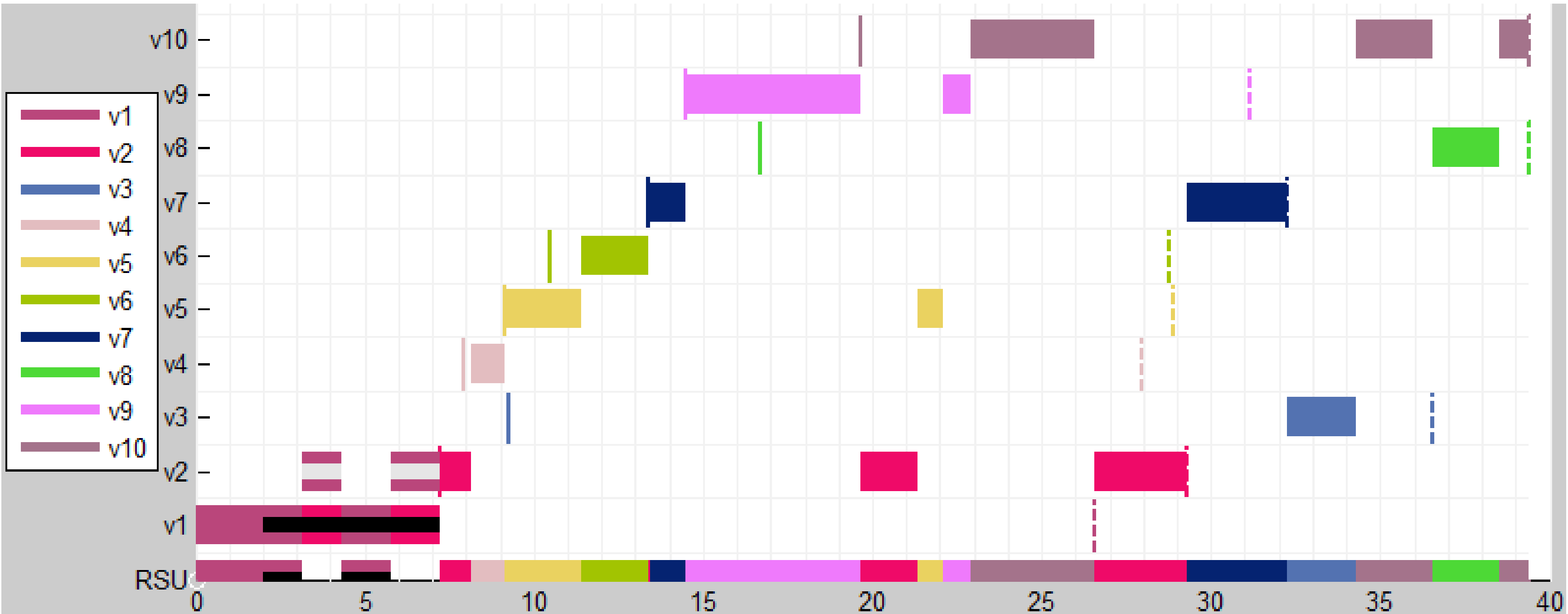


Figure 4.5: Scheduling of scenario in Fig. 4.4(d) where the proposed model achieved %93.4 utilization.

5. CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

This thesis proposes a novel scheduling model for downlink and uplink utilization in clustered vehicular networks. Total amount of data that can be transferred between RSU and cluster was aimed to be increased with making use of V2V2R communications. Simulations showed that the contribution of V2V2R communications enables proposed model to utilize communication channel better than existing scheduling algorithms such as EDF or FCFS. Under realistic assumptions, proposed models were able to almost fully utilizing communication channel. This is achieved by an efficient V2V2R and V2R scheduling model which turns the resource sharing problem into a linear programming problem in a scalable manner.

5.2 Future Work

For the future, a model that can handle both uploads and downloads in the same scheduling policy which also allows chains of V2V communications can be designed. This model requires uplink scheduling policy to be determined with only linear programming, without preprocessing the model by another scheduling policy. As an extension, scheduling of the communications after leaving RSU coverage can be modelled. This approach requires a probabilistic model that can estimate future directions of the vehicles, as well as their future velocity.

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CURRICULUM VITAE

Name Surname: SALIH SERDAR GUCLU

Place and Date of Birth: DINAR - 11.07.1989

Adress: İTÜ Bilgisayar ve Bilişim Fakültesi Laboratuar-3 Sarıyer/İSTANBUL

E-Mail:guclusa@itu.edu.tr

B.Sc.: İstanbul Technical University, Computer Engineering, 2011 June

List of Publications and Patents:

PUBLICATIONS/PRESENTATIONS ON THE THESIS

- Guclu, S. S. and Altilar, D. T. (2014). Uplink Utilization with V2V2R Communications in Clustered Vehicular Networks, IEEE Wireless Communications, Vehicular Technology, Information Theory and Aerospace & Electronic Systems (VITAE).
- Guclu, S. S. and Altilar, D. T. (2014). Downlink Utilization with R2V2V Communications in Clustered Vehicular Networks, IEEE/IET International Symposium on Communication Systems, Networks & Digital Signal Processing (CSNDSP'14)