CLUSTER DESIGN FOR INTER-VEHICLE COMMUNICATION

(ARAÇLAR ARASI HABERLEŞME İÇİN KÜME YAPISI TASARIMI)

by

Ömer KAYIŞ, B.S.

Thesis

Submitted in Partial Fulfillment

of the Requirements

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This thesis serves as documentation for my work during the last year of M.S. Program in Computer Engineering, at Institute of Sciences, Galatasaray University. It presents CF-IVC (Cluster Formation for Inter-Vehicle Communications), a novel clustering approach for vehicular ad-hoc networks. CF-IVC was designed to increase overall network efficiency by assigning special roles to nodes (in our case, vehicles) according to their speed information.

First of all, I would like to express my deepest sense of gratitude to my supervisor, Yrd. Doç. Dr. Tankut Acarman who offered invaluable support and guidance through the duration of this work.

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Ömer KAYIŞ

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List of Symbols

ACK	: Acknowledgment
BC	: Basic Channel
BER	: Bit Error Rate
BTMA	: Busy Tone Multiple Access
C2C CC	: Car 2 Car Communication Consortium
CF-IVC	: Cluster Formation for IVC
CH	: Clusterhead
CSMA/CA	: Carrier Sense Multiple Access with Collision Avoidance
CTS	: Clear to Send
CW	: Contention Window
DBTMA	: Dual BTMA
DCF	: Distributed Coordination Function
DIFS	: DCF Inter Frame Spacing
DS	: Data Sending
FCC	: Federal Communications Commission
FI	: Frame Information
GNSS	: Global Navigation Satellite System
GNU	: GNU is Not Unix
GPS	: Global Positioning System
GW	: Gateway
INIT	: Initial
ITS	: Intelligent Transportation System
IVC	: Inter-Vehicle Communication
LAN	: Local Area Network
LIDAR	: Light Detection and Ranging
LLC	: Logical Link Control

MAC	: Medium Access Control
MACA	: Multiple Access Collision Avoidance
MACAW	: MACA for Wireless
MCS-CDMA	: Multi-code Sense CDMA
MF	: Mobility Framework
MPSG	: Maximum Perceived Speed Group
NAV	: Network Allocation Network
NoW	: Network on Wheels
ORD	: Ordinary
OSI	: Open Systems Interconnection
PATH	: Partners for Advanced Transit and Highways
PC	: Passive Clustering
PN	: Pseudo-noise
QoS	: Quality of Service
R-ALOHA	: Reservation ALOHA
RR-ALOHA	: Reliable r-ALOHA
RSSI	: Received Signal Strength Indicator
RTD&D	: Research, Technological Development and Demonstration Activities
RTS	: Request to Send
RVC	: Road-to-Vehicle Communication
S-ALOHA	: Slotted ALOHA
SIFS	: Short Inter Frame Spacing
TCP / IP	: Transmission Control Protocol / Internet Protocol
TD-CDMA	: Time Division – Code Division Multiple Access
TX power	: Transmission power
UMTS	: Universal Mobile Telecommunications System
US	: United States
UTRA-TDD	: UMTS Terrestrial Radio Access-Time Division Duplexing
V2V	: Vehicle-to-Vehicle Communication
VANET	: Vehicular Ad-Hoc Network
WAN	: Wide Area Network
WAVE	: Wireless Access in the Vehicular Environment

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Abstract

Good progress has been made in wireless technologies over the last decade. Reduced manufacturing cost and great popularity of Internet / cellular services have allowed the proliferation in small computing devices with wireless communication capabilities. Many new services may profit from these advancements; consequently, research groups, both from academia and industry, are interested in ad hoc networking applications.

The term ad hoc networking indicates a kind of wireless network where a predefined communication infrastructure does not exist. It also points the decentralized and self-organizing nature of the network, in other words each node is responsible for establishing dynamic connections with the nearby nodes without the intervention of a central authority.

Recently, vehicular ad hoc networks (VANET) are introduced by the research community. VANET is a special subset of mobile ad hoc networks where nodes are cars and other vehicles; and networking environment consists of streets, roads and highways. The essential technologies fall into two major categories: infrastructure to vehicle (I2V) and vehicle to vehicle (V2V) communications. In this thesis, the focus is primarily kept on the latter.

The primary purpose of VANETs is the deployment of safety-related applications divided into three main groups: driver assistance, information and emergency warning services. Additionally, various commercial applications may be deployed as well by exploiting the underlining technology. Lately, many research initiatives have been started by universities in partnership with car manufacturers.

Typically, safety applications require very little latency instead of high data rates. This, in conjunction with particular characteristics of VANET such as high mobility and dynamic network topology, brings unique research challenges. To overcome related issues, a layered approach has been adopted as in TCP/IP architecture:

- In physical layer, Dedicated Short Range Communications spectrum has been allocated by FCC in United States. It consists of a 75 MHz of spectrum at 5.9 GHz range; unfortunately such a continuous band does not exist in Europe, thus several smaller bands are combined together to allow for harmonization with US.
- Concerning the medium access, MAC protocols used in other types of wireless networks are not applicable in VANETs. Conventional authentication-authorization schemes cause large overhead and latency. Therefore, new contention-free medium access protocols should be devised in order to minimize packet collisions and also acknowledgment procedures should be integrated into this layer to satisfy hard delay constraints
- Routing in VANETs is a subject that needs special attention and extensive studies. In a typical scenario, VANETs consist of hundreds of vehicles and more than that number during rush hours and in city centers. Even though broadcasting schemes such as flooding eventually deliver packets to the destination node, they are not effective and prone to causing collisions. New approaches such as geographic forwarding where packets are delivered to each node in a specific zone or trajectory forwarding where packets are directed along predefined trajectories should be adopted. Besides, a dynamic route from a node to another is not guaranteed due to the changeable driver behavior and high mobility. Therefore, a node may store a packet instead of relaying it directly and forward it when an end-to-end route becomes available.

Cluster formation for IVC (CF-IVC) presented in this thesis intends to control medium access of the nodes and form a virtual backbone for routing by dividing the network into smaller manageable groups. It offers all the benefits of clustering such as spatial reuse of resources and a scalable network since overall network appears smaller and more stable to each mobile terminal. CF-IVC also introduces a new mechanism to handle mobility and the allocation of reusable orthogonal codes to each node provides a contention-free medium access control.

The proposed protocol was evaluated by a simulation scenario that runs on top of the OMNeT++ platform and the obtained results show that CF-IVC reaches its intended goals at a reasonable cost.

Résumé

Un bon progrès a été accompli en technologies sans fil pendant la dernière décennie. Le coût de fabrication réduit et la grande popularité de l'Internet/des services cellulaires ont permis la prolifération dans de petits dispositifs informatiques avec des capacités de transmission sans fil. Plusieurs services nouveaux peuvent profiter de ces progrès; par conséquent, les groupes de recherche, du milieu universitaire comme de l'industrie, sont intéressés par des applications ad hoc.

Le terme « ad hoc» indique un genre de réseau sans fil où une infrastructure prédéfinie de communication n'existe pas. Cela aussi indique une nature de réseau décentralisée et auto organisée, autrement dite chaque noeud est responsable d'établir des connexions dynamiques avec les noeuds voisins sans l'intervention d'une autorité centrale.

Récemment, les réseaux ad hoc véhiculaires (VANET) sont introduits par la communauté de recherches. VANET est un sous-ensemble spécial de réseaux ad hoc mobiles où les noeuds sont des voitures et d'autres véhicules ; et l'environnement d'interconnexion se compose des rues et des routes. Les technologies essentielles se divisent dans deux catégories principales : d'infrastructure à véhicule (I2V) et de véhicule à véhicule (V2V). Dans cette thèse, le centre d'intérêt est principalement la dernière catégorie.

Le but primaire de VANET est le déploiement des applications liées à la sécurité qui sont divisées en trois groupes principaux : assistance au conducteur, information et services d'avertissement de secours. Cependant, de diverses applications commerciales puissent être bien déployées en exploitant la technologie sous-jacente. Récemment, beaucoup d'initiatives de recherches ont été commencées par des universités dans le partenariat avec des constructeurs de voiture.

Typiquement, les applications de sécurité exigent peu de latence au lieu des taux élevés de données. Ceci, conjointement avec des caractéristiques particulières de VANET comme la mobilité élevée et la topologie dynamique de réseau, apporte des enjeux particuliers de recherches. Pour surmonter les problèmes relatives, une approche superposée a été choisie comme dans l'architecture de TCP/IP :

- Dans la couche physique, le spectre des communications dédiées à courte distance a été affecté par FCC aux Etats-Unis. Il se compose d'un spectre de 75 mégahertz à la gamme 5.9 gigahertz; malheureusement une bande si continue n'existe pas en Europe, ainsi plusieurs plus petites bandes sont combinées ensemble pour permettre l'harmonisation avec les Etats-Unis.
- En ce qui concerne l'accès au support, les protocoles de MAC utilisés dans d'autres types de réseaux sans fil ne sont pas applicables aux VANETs. Les procédés conventionnels de l'autorisation et d'authentification causent de grands « overhead » et de latence. Par conséquent, de nouveaux protocoles d'accès moyens sans conflit doivent être conçus afin de réduire au minimum les collisions de paquets et également, les procédures d'acquisition doivent être intégrées dans cette couche pour satisfaire les contraintes de retard.
- Le routage dans VANETs est un sujet qui nécessite une particulière attention et des études plus profondes. Dans un scénario typique, VANETs se composent de centaines de véhicules et plus de ce nombre pendant des heures de pointe et aux centres de ville. Quoique les procédés de communication tels que l'inondation éventuellement livrent les paquets au destinataire, ils ne sont pas effectifs et enclins à causer des collisions. De nouvelles approches telles que l'expédition géographique où les paquets sont délivrés à chaque noeud dans une zone géographique ou de trajectoire spécifique où les paquets sont dirigés le long des trajectoires prédéfinies devraient être adoptées. En outre, un chemin dynamique d'un noeud à un autre n'est pas garanti dû au comportement changeable du conducteur et à la mobilité élevée. Par conséquent, un noeud peut conserver un paquet au lieu de le transmettre directement et l'expédier quand un chemin bout à bout devient disponible.

La formation des segments pour IVC (CF-IVC) présentée dans cette thèse est prévue pour contrôler l'accès moyen des noeuds et pour former un réseau principal virtuel en divisant le réseau en plus petits groupes gérables. Cela offre tout l'avantage de segmenter le réseau comme la réutilisation spatiale des ressources et un réseau évolutif puisque le réseau global semble plus petit et plus stable à chaque terminal mobile. CF-IVC introduit un nouveau mécanisme pour s'occuper de la mobilité et l'allocation des codes orthogonaux réutilisables à chaque noeud fournit un contrôle d'accès moyen sans conflit.

Le protocole proposé a été évalué par un scénario de simulation qui fonctionne sur la plateforme d'OMNeT++ et les résultats obtenus montrent que CF-IVC atteint ses buts destinés à un coût raisonnable.

Özet

Son 10 yılda kablosuz iletişim teknolojilerinde çok büyük ilerlemeler kaydedilmiştir. Bununla birlikte, azalan üretim maliyetleri ve hücresel / Internet hizmetlerine olan büyük ilgi kablosuz iletişim yeteneğine sahip pek çok taşınabilir aletin hayatımıza girmesine sebep olmuştur. Tüm bu gelişmeler, bugüne kadar tanık olmadığımız birçok yeni uygulamanın geliştirilmesi için gerekli ortamı hazırlamıştır. Bu uygulamaların merkezinde son zamanlarda akademik camia ve büyük endüstriyel araştırmacıların da yakından ilgilendiği, belli bir servis sağlayıcının hizmetine ihtiyaç duyulmadan haberleşmeyi sağlayan ad-hoc ağlar vardır.

Ad-hoc ağlar belli bir altyapının bulunmadığı ya da kurulmasının mümkün olmadığı yerlerde iletişimi mümkün kılabilecek kablosuz ağlara verilen genel isimdir. Ağın yapısı dağıtıktır; ağı oluşturan tüm düğümler gerektiğinde merkezi bir sunucuya ya da düzenleyiciye ihtiyaç duymadan dinamik bağlantılar oluşturabilecek donanıma sahiptir.

Son dönemde ad hoc ağlar alanında yapılan çalışmalar özellikle algılayıcı ağlar ve yol ad-hoc haberleşmesi tasarımı üzerinde yoğunlaşmıştır. Algılayıcı ağlar, bulundukları ortamdaki fiziksel koşulları kaydederek bu verileri bir bilgi işlem merkezine yönlendiren düğümlerden oluşur. İkinci grupta ise adından anlaşılacağı üzere düğümler otomobiller ve diğer araçlardır. Burada ağ tasarımını iki temel haberleşme modeline ayırabiliriz: araçlar arası haberleşme ve araç – altyapı haberleşmesi. Bu çalışmada özellikle araçlar arası haberleşme üzerinde durulmuştur.

Sadece Avrupa'da yılda ortalama 40.000 kişinin trafik kazaları yüzünden hayatını kaybettiği ve buna eklenen yaralı sayısı ile maddi kayıp hesaba katıldığında araçlar arası ağların asıl amacının sürücü ve yolcu güvenliğini sağlamak olması hiç de şaşırtıcı değildir. Bunun la birlikte geliştirilen teknolojiler farklı ticari uygulamaların hizmete

sunulmasına olanak sağlayacaktır. Son zamanlarda üniversite ve otomobil üreticilerinin bir araya gelerek oluşturduğu konsorsiyumlar sayesinde bu alandaki çalışmalar hız kazanmıştır.

Tipik olarak güvenlik uygulamaları büyük veri değerlerindense düşük gecikmelere ihtiyaç duyar. Yapılan benzetimler göstermiştir ki bir çarpışma olduğunda zincirleme kazanın önlenmesi için 500 metre yarıçapa sahip bir çember içindeki tüm araçlar 0.5 saniye içerisinde bu durumdan haberdar olmalıdır. Ancak bunu başarmak, yüksek hızla hareket eden araçlar, değişken topoloji, ortamdaki engeller (bina, tünel, köprü vs.) gibi karakteristik özellikler göz önüne alındığında oldukça zordur. Tüm bu zorlukları aşmak için TCP/IP mimarisinde olduğu gibi çok katmanlı bir yapı benimsenmiştir:

- Fiziksel katmanda, Amerika Birleşik Devletleri'nde 5,9 GHz seviyesinde 75 MHz'lik bir frekans bandı Federal Haberleşme Komisyonu tarafından kısa mesafeli telsiz haberleşme için tahsis edilmiştir. Ancak ne yazık ki bu şekilde kesintisiz bir bant Avrupa'da mevcut değildir. Aynı sistemlerin her iki coğrafyada da iş görebilmesi için ETSI (European Telecommunications Standards Institute) tarafından daha küçük boyuttaki birkaç bandın yine 5,9 GHz seviyesinde birleştirilmesi önerilmiştir.
- Diğer kablosuz ağlarda kullanılan MAC protokolleri araç ağlarındaki düğümlerin haberleşme ortamına erişimini düzenlemek için yeterli değildir. Bu tip protokollerde kullanılan konvansiyonel kimlik doğrulama ve yetkilendirme metotları fazla işlem yüküne ve gecikmeye sebep olur. Sonuç olarak, gecikme kısıtlarını karşılayacak ve paket çakışmalarını önleyecek yeni erişim yöntemlerinin geliştirilmesi gereklidir. Ayrıca gönderildi bilgisini taşıyacak mekanizmanın bu katmanda gerçeklenmesi düğümde harcanacak işleme zamanını daha da azaltabilir.
- Genellikle araç ağları binlerce düğümden oluşur. Bu durumda, sel algoritması gibi yayımlama yöntemleri paketi er geç göndericiden alıcıya ulaştırsa da çok fazla kaynak kullanımına ve paket çarpışmasına yol açar. Otoyolları takip eden coğrafi yönlendirme gibi yeni yaklaşımlar paketleri belli bir bölgede yer alan tüm düğümlere göndererek daha ekonomik ve etkin bir mekanizma sağlar. Öte yandan, değişken topolojiye bağlı olarak iki düğüm arasında uçtan uca bir bağlantı bulmak her zaman mümkün

olmayabilir, böyle bir durumla karşılaşıldığında gönderilecek paketin tampon belleğe alınarak bağlantı kurmanın mümkün olduğu bölgeye taşındıktan sonra iletilmesi kaynak kullanımını önemli ölçüde azaltacaktır.

Bu tezin konusu olan CF-IVC protokolünün amacı araç ağlarını yönetimi kolay daha küçük parçalara bölerek haberleşme ortamına erişimi düzenleyip sanal bir yönlendirme omurgası oluşturmaktır. Kaynakların yeniden kullanılması ve ölçeklendirilebilirlik gibi kümeleme yapısının tüm avantajlarına sahip olmakla birlikte yeni geliştirilen harekete dayalı topoloji kontrolü, dikey kodların kullanılmasıyla paket kayıplarını en aza indiren bir erişim kontrolü sağlamaktadır.

OMNeT++ platformunda hazırlanan benzetim CF-IVC'nin yukarıda sayılan faydalarını kabul edilebilir bir maliyetle sağladığını göstermiştir.

1. Introduction

Major progress was made in wireless communication technologies in the recent past. One particular domain that may exploit these modern developments is Intelligent Transportation Systems (ITS). In ITS technologies, vehicle communication or car talk is an important research area. Gathering information from the neighboring vehicles, from the infrastructure, toll collection or interactive entertainment, chat with the other travelers in the neighborhood may significantly improve driving safety, traffic efficiency, comfort and pleasure.

Safety enhancement and traffic efficiency, contributed by vehicle communication, may be in terms of extending the perception limits of the driver. In order to increase perception limits and at the same time to help decrease reaction limits, inter-vehicle communication (IVC) or road-to-vehicle communication (RVC) is introduced. IVC entails the communication between two or more vehicles, whereas RVC involves traffic monitoring and management services i.e., exchange of road, traffic information or electronic toll collection systems while navigating. Different communication technologies including Bluetooth, wide area network (WAN) through 802.11b wireless technology have been used for exchanging information among the vehicles and infrastructure.

Although intense research efforts are made on clustering in wireless ad hoc / sensor networks, clustering is not extensively studied in IVC. A clustering approach has following benefits: First, clustering facilitates the spatial reuse of resources, thus increases the system capacity. Second, special nodes in clusters (clusterheads and gateways) form a virtual backbone for routing, and last, since only local information is needed, the network appears smaller to each mobile terminal. The above advantages are also valid for IVC networks. Consequently, clustering may be considered to create more scalable and stable communication schemes.

Up to date, in IVC communications, clustering is solely used for platooning where a group of vehicles pursue the same direction for a common purpose, or for grouping vehicles moving on the same lane. In these two cases, nodes should make extra efforts to maintain the cluster formation, (e.g. always follow the leader etc.) whereas for the most of the time driver behavior is random and unpredictable.

In this work, clustering formation for group communication in IVC is presented. Considering mobility, presented clustering protocol assigns tasks to the vehicles desiring to communicate. Since under heavy traffic, existing clustering performance is degraded due to possible data packet collision in the same time slots, Code Division Multiple Access (CDMA) scheme is used to assign orthogonal codes to the *a priori* identified vehicular nodes. Based on hierarchical setup of clustering and identification of vehicles, appropriate code assignment may be accomplished. Hence, data packet collisions and primary code collisions due to accessing to the same channel are avoided. Based on Cluster Formation for IVC (CF-IVC) with assigned code access may be a promising media access control for IVC applications.

The remainder of this thesis is organized as follows. Chapter 1 provides an overview of vehicular ad-hoc networks. Chapter 2 presents world-wide research efforts on IVC. In Chapter 3, promising MAC protocols that may be adopted for V2V communication are listed. Chapter 4 explains CF-IVC in detail. Finally, the proposed scheme is evaluated by a simulation program that runs on top of OMNeT++ platform and results are given in Chapter 5.

2. Vehicular Ad-Hoc Networks

Vehicular ad-hoc network is an emerging new technology to provide communication between vehicles and nearby infrastructure-based (roadside) equipments by the means of wireless networking technologies. It constitutes a subset of mobile ad-hoc networks, which may be seen as a form of wireless ad-hoc networks.

The term “ad-hoc” (lat. “to this”) points the decentralized and self-organizing nature of the network; that is, each node may work as a router in such a network to relay packets from source to destination and connections may be reestablished dynamically without the intervention of a central authority in case they are lost.

Back in 1970s and 1980s the research on ad-hoc networking was purely for military purposes **[1]**. At that time, the main goal was to set up a communication network in a hostile environment, where no infrastructure is available. Since 1990s, with the proliferation of small size information processing devices and the increasing need to exchange digital information, ad hoc networking has become an important research topic to exploit its commercial potential in urban areas. The emerging technologies in wireless technologies, such as Bluetooth, wireless LAN allow ad-hoc networking to become a promising solution in order to increase the radio coverage of broadband wireless systems and to extend the multimedia services to wireless environments.

Ad hoc networks may be deployed as a stand-alone isolated network or may be integrated with larger infrastructure-based networks.

In **[2]**, Xu and Hischke state that large scale ad hoc networks have little commercial potential because they are not suited to be used as communication network that needs to transport a large amount of information. The authors say that the usual authentication-authorization-accounting mechanism is infeasible to be implemented due to the lack of a central control server. Also, flooding of route request may use the majority of resources especially if there are some mobile networks; and finally the traffic performance decreases with the increase of mean hops of connections. Therefore, small size isolated ad hoc networks are commercially more promising and may take significant role in connecting home appliance, portable devices during meetings etc.

By different application types, wireless ad hoc networks are classified as follows:

- Mobile ad hoc networks
- Wireless sensor networks
- Wireless mesh networks

Wireless mesh networks consist of mesh routers and mesh clients, where mesh routers have minimal mobility and form the backbone of the network. Wireless sensor networks are made up of many sensors and several gateways to cooperatively monitor physical or environmental conditions and relay gathered data to special information processing nodes. Due to their characteristics, wireless mesh networks and wireless sensor networks are beyond the scope of this work. Provided that, these technologies are often used together in practical applications; for example, on-board monitoring devices form a sensor network inside a vehicle. Events triggered by several conditions (air bag opened, sudden break etc.) are processed and resulting information is sent to neighboring vehicles by the transceiver.

2.1. VANET Connectivity

In physical layer, the spectrum allocation is a major issue because the spectrum availability during the intended usage period has to be guaranteed. In United States, Federal Communications Commission has already allocated Dedicated Short Range Communications spectrum (75 MHz of spectrum at 5.9 GHz range (5.850 to 5.925 GHz)) to be used for vehicle-to-vehicle and vehicle-to-infrastructure communications. This frequency band is also available for commercial applications as long as they do not interfere with its primary use. Due to the fact that a continuous band of 75 MHz at 5.9

GHz range does not exist in Europe the spectrum is composed of several smaller bands to allow for harmonization with US. Figure 2.1 sums up the world-wide spectrum allocations.

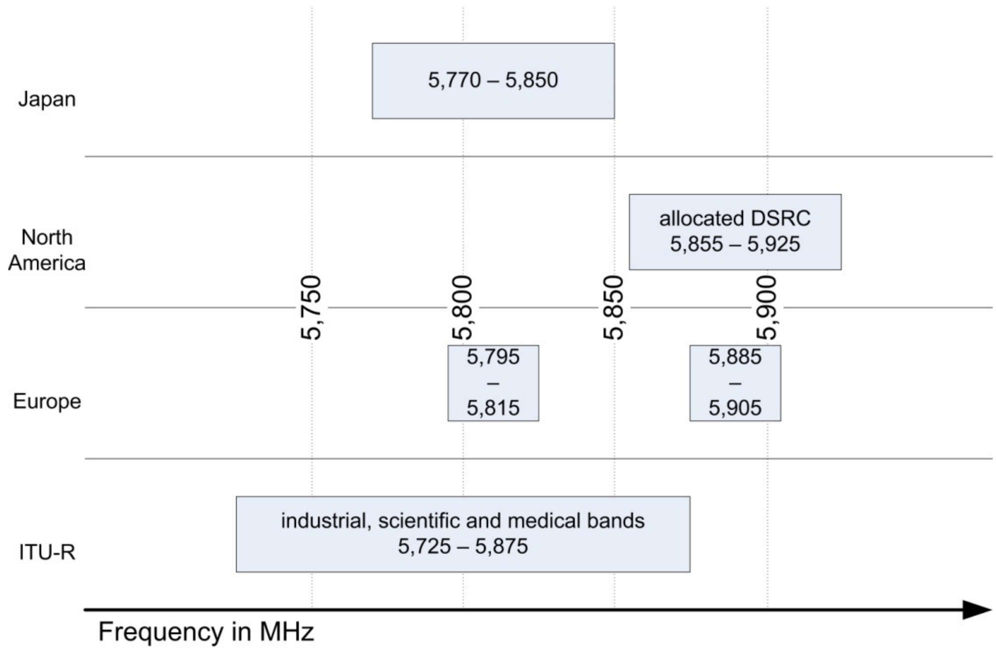

Figure 2.1 World-Wide Spectrum Allocations

For wireless access, there are three main methods that may be adopted for VANETs. The first method is wireless LAN / cellular architecture in which the connectivity among the vehicles is provided by fixed roadside gateways. Although, third generation (3G) technology achieves good coverage and reliable security it is proven to be infeasible concerning the infrastructure costs involved. Besides, allocated bandwidth is limited and the authentication process causes increased latency.

An alternative to this is to perform pure ad-hoc communication between vehicles. Lower latency and no service provider cost are the main advantages of ad-hoc scheme. Unfortunately, current communication algorithms are not mature enough yet for the market penetration. Nevertheless, this seems to be the most promising method in long term.

A hybrid architecture would benefit from both the lower cost / latency of ad-hoc scheme and the reliability of wireless LAN standards. In such design, although the primary method of communication is pure ad-hoc, zones that need special attention (blind crossing etc.) would be supplied with stationary roadside units in order to improve communication efficiency.

2.2.Research Challenges

Fundamental differences from other mobile ad-hoc networks lead to unique challenges to overcome by the academia and industry. In their paper **[3]**, Jakubiak and Koucheryavy list some of the major issues that need to be resolved. Beside the wireless access standards and spectrum allocation decisions following issues have to be addressed by the research community:

- Broadcasting and message dissemination: As broadcasting will be the primary mean to propagate information in VANET applications, efficient packet forwarding schemes are required. The vast number of duplicated packets resulting from the utilization of conventional flooding methods would cause contention that limits dramatically network throughput. A more efficient way would be to limit the number of nodes that participate in relaying process either by forming clusters or by using location-aware broadcasting in which packets are propagated only into a zone of relevance.
- Routing issues: Since the driver behavior is unpredictable and the vehicle speeds are various, one cannot assume that an end-to-end connection can always be established between a source and a destination. In a highway scenario, a routing route cannot be always created between “isolated islands” of vehicles, thus new concepts such as trajectory based forwarding or caching schemes should be developed.
- Power Management: Energy efficiency is not a concern in VANETs, consequently research efforts should concentrate on transmission power (TX power) adjustment rather than energy saving methods. If TX power is too high, it may cause interferences at nearby nodes, thus disrupting other

communications; if it is too low, it may create isolated groups, which affects severely the network connectivity. Therefore, a favorable TX power should be a decided according to the network density. Ongoing researches intend to keep the number of 1-hop neighbors within the optimum maximum and minimum values **[4-5]**.

- Security and Privacy: As the majority of intended VANET applications are safety related, fake messages or interference attempts by third-parties should be averted. Also, anonymity should be preserved in order to protect users' privacy.

2.3.VANET Characteristics

VANETs share common similarities as all subsets of mobile ad-hoc networks: such as self-organization capabilities, limited bandwidth and short radio transmission range. However following characteristics distinguish them from the other mobile ad-hoc networks:

- Dynamic topology: Due to high relative speed between vehicles, the topology of the network is always changing. In an average case, the transmission link between two nodes last less than 20 seconds. For that reason, approximation of link lifetime is needed. This way, new routes may be established before the links are broken in order to maintain network connectivity. In **[6-7]** authors found a reasonable solution nevertheless it works only for limited cases. Another solution may be deploying some fixed units for an additional cost.
- Mobility: Although vehicles are often constrained by pre-built highways, road or streets, it is very hard, if not possible, to define an exact relationship between vehicular mobility and network connectivity because of the driver decisions.
- No power constraints: As the nodes in VANETs are cars or fixed infrastructure units, they have ample energy. Thus, energy consumption is not an issue; instead transmission power has to be adjusted to maintain connectivity and to prevent interference.

- Scale / Density: In a typical scenario, the environments for VANETs are highways where hundreds of vehicles may be present in a relatively small area. Moreover, in road portions where congestion occurs the network density will increase drastically which will result in augmented possibility of contention.
- Delay constraints: Most of the intended VANET applications are safety related, thus they require little latency instead of high data rates. For example, in case of a hard brake, message carrying this event has to be propagated in a 500 m radius area in 0,5 second. In this kind of applications, instead of average delay, the maximum delay is crucial.

2.4.VANET Applications

Integrated network interfaces, on-board sensors and ample computing power allow numerous services to be deployed. These services are divided into two groups: safety-related and commercial applications.

Safety-related applications are the primary purpose of the inter-vehicular communications. The basic idea is to extend the range of perception of the driver. They are studied under three main headings:

- Assistance: platooning, navigation, merging point / lane-changing assistance, cooperative collision avoidance, intersection coordination etc.
- Information: Speed limit, work zone information etc.
- Emergency warning: accident reporting, road condition warnings etc.

The underlying technology developed for safety-related applications may be also used for the deployment of new commercial services. This kind of services is intended to improve passenger comfort and traffic efficiency. Point-of-interest (gas stations, restaurants etc) localization, weather information, interactive communication between passengers and wireless advertising would be first to profit from VANET technologies. In addition, all sorts of services that run on top of TCP/IP stack may be deployed with possible Internet integration.

3. Research and Projects

The promises of wireless communication to support traffic safety applications - concerning over 700.000 road fatalities every year in the world- and several commercial uses have drawn a significant attention from both academia and industry. Lately, universities and car manufacturers around the world have been working together to develop new technologies to prevent road accidents and to ensure a more enjoyable driving experience. One of the earliest researches in inter-vehicular and vehicle-to-infrastructure communication was led by Association of Electronic Technology for Automobile Traffic and Driving in Japan in the early 1980s **[8]**. Although extensive studies have been made since then, global standards are yet to be defined. Below, recent project groups and studies are listed:

- **California PATH**: California PATH (Partners for Advanced Transit and Highways) **[9]** was established in 1986 in US and administered by the Institute of Transportation Studies, University of California, Berkeley and California Department of Transportation. PATH research is divided into four program areas:

- Policy and Behavioral Research
- Transportation Safety Research
- Traffic Operation Safety Research
- Transit Operations Research

PATH has 45 full-time staff members and supports the projects of nearly 50 faculty members and 90 graduate students. As of April 2008, there are 65 such projects.

- **Promote-Chauffeur**: Promote-Chauffeur **[10]** is a part of the 4th Framework Programme for Research, Technological Development and Demonstration Activities (RTD&D) of the European Union. The project plans on decreasing the workload on truck drivers and increasing the traffic safety by the means of a “tow bar” which links two trucks electronically. Furthermore, the concept has been extended to platooning where a group of vehicles pursue the same direction for a common purpose. As a test bed, two operative pairs of trucks have been constructed and equipped with necessary components such as sensors and vehicle controller subsystem, and then they have been evaluated under real-life conditions on the Brenner highway. In 2000, Promote-Chauffeur II **[11]** has been launched as a part of the Sixth Framework Programme.

- **CarTALK 2000**: CarTALK 2000 **[12],** which is funded within the Information Society Technologies Cluster of the 5th Framework Program of the European Commission, started in August 2001. The main objectives are the development of co-operative driver assistance systems and the development of a self-organizing ad-hoc radio network.

CarTALK 2000 divides its applications into three groups:

- Information and Warning Functions: This group of applications consists of early warning mechanisms. Incidents and road conditions, such as accidents, vehicle breakdown, traffic density or congestions are propagated by the means of inter-vehicular communication schemes. These are typically pure vehicle-to-vehicle applications; hence infrastructure-based environment sensing devices are not required. Other uses are blind-spot warning and intersection assistance.
- Communication-based Longitudinal Control: Although adaptive cruise control systems exist, their capabilities are only limited to reactions on the vehicle directly in front. CarTALK 2000 intends to help drivers to be aware of "invisible" vehicles by integrating communication devices.
- Co-operative Assistance Systems: CarTALK 2000 also aims to devise methods to exchange information between vehicles to assist driver in critical decision making at highway entries and merging points.

Concerning the communication systems, the dynamic topology of vehicular networks and the high velocities of mobile nodes have been taken into account while adopting appropriate solutions. Based on TD-CDMA, a new mobile data network standard called

UTRA-TDD **[13]** (UMTS Terrestrial Radio Access-Time Division Duplexing) has been developed. The medium access control, the radio link control, the broadcast/multicast control and the packet data convergence protocol belong to the layer 2 of the UTRA network, UTRAN. The radio resource control represents the layer 3 protocol which belongs to Access Stratum.

As the communication frequency interval, Short Range Device band (869,4-869,65 MHz), which can satisfy the large communication zone requirement by Information and Warning Functions, has been chosen.

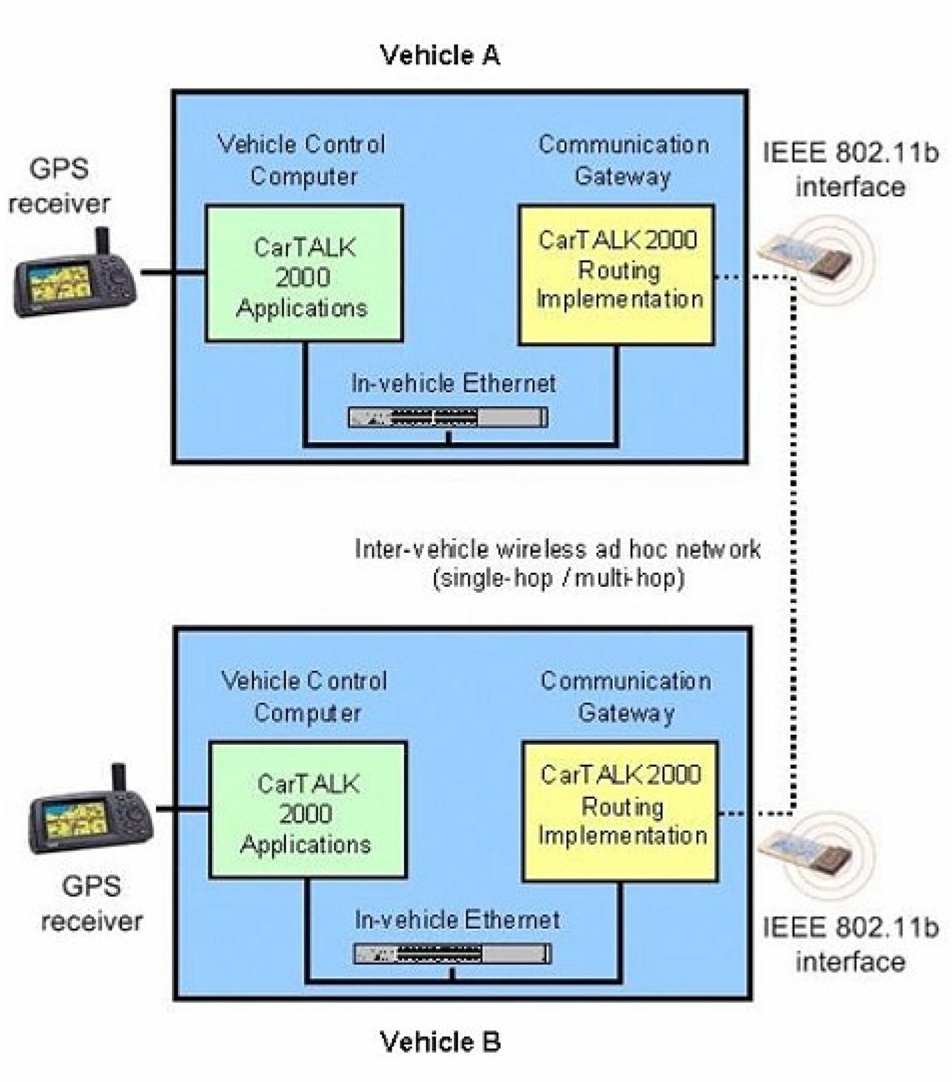

Figure 3.1 CarTALK routing architecture

On top of the lower ISO OSI layer, a decentralized ad hoc routing protocol has been implemented. Taken from the CarTALK 2000 website, Figure 3.1 illustrates the related routing architecture.

Beside the technological issues, CarTALK 2000 also investigates the market potential and legal aspects to bring developed systems to the European market.

- **Car 2 Car Communication Consortium**: Car 2 Car Communication Consortium (C2C CC) **[14]** is a non-profit organization dedicated to increase road traffic safety and efficiency by means of inter-vehicular communications. The organization has been founded by major vehicle manufacturers in Europe and grown with the participation of suppliers, research organizations and other partners.

The main objectives of C2C CC are **[15]:**

- To establish an open industry standard for vehicle-to-vehicle communication systems in Europe
- To guarantee inter-vehicle operability
- To develop active safety applications
- To promote the allocation of a royalty free European-wide frequency band for vehicle-to-vehicle applications
- To develop deployment strategies and business models to speed-up the market penetration.

Applications and underlining communication systems are developed according to use case scenarios which are regrouped under safety, traffic efficiency and comfort (information / entertainment) headings:

- Cooperative forward collision warning
- Pre-crash sensing / warning
- Hazardous location V2V notification
- Enhanced route guidance and navigation
- Green light optimal speed advisory
- V2V merging assistance

- Internet access in vehicle
- Point of interest notification
- Remote diagnostics of the state of vehicles

C2C Communication System contains three distinct domains. The *in-vehicle domain* is composed of an on-board unit and application units. The *ad hoc domain* consists of on-board communication units and road-side units to create a V2V communication networks. The *infrastructure domain* refers to internet access nodes or other fixed servers deployed for either public or commercial purposes.

Concerning C2C Communication architecture, in the physical layer the following frequency band allocations have been suggested: 10 MHz band from 5.885-5.895 GHz interval for network control and critical safety applications; 10 MHz band from 5.895-5.905 GHz interval for critical safety applications; three 10 MHz bands from 5.875-5.885 GHz and from 5.905-5.925 GHz intervals for road and traffic efficiency applications; and two 10 MHz bands from 5.855-5.875 GHz interval for non-safety applications. The C2C MAC/LLC layer is based on IEEE 802.11p **[16]** and IEEE 1609.4 **[17]** protocols and CSMA/CA is adopted as the MAC algorithm. The related network layer specifies three data delivery strategies:

- Event-driven geographical broadcast where data packets are propagated to all nodes within a geographical area
- Event-driven single hop broadcast where data packets are delivered to all one-hope far (neighboring) nodes
- Periodically sent beacon packets

\- **Network on Wheels**: Network on Wheels (NoW) **[18]** is a German project which was initiated in 2004 by Daimler AG, BMW AG, Volkswagen AG, Fraunhofer Institute for Open Communication Systems, NEC Deutschland GmbH and Siemens AG.

Main objectives of NOW are:

- Creation of communication protocols and data security algorithms for inter-vehicular communication systems

- Support for active safety applications, comfort applications with infrastructure and between vehicles
- Development of radio systems based on IEEE 802.11 standards
- Standardization with the Car 2 Car Communication Consortium
- Market investigation and business model planning

- **PReVENT**: PReVENT **[19]** is a European automotive industry activity co-funded by the European Commission to contribute to road safety by developing and demonstrating preventive safety applications and technologies.

Interaction of safety applications with the driver has been separated in multiple phases according to the significance and timing of the threat:

- Normal driving phase: No threat in the vicinity
- Information phase: If a threat is sensed the driver is informed by the means of digital map-based and cooperative systems
- Warning phase: If there is no driver reaction, she / he is warned by using more significant methods such as acoustic interaction
- Assistance phase: Assistance or intervention to avoid a possible accident (break assistance, active vehicle control etc.)
- Pre-crash phase: Reduction of the severity if an accident is inevitable

To achieve the above mentioned effects, PReVENT makes use of the following:

- Sensing technologies for environment perception (infrared sensing, image perception, LIDAR / RADAR sensors, gyro sensors for motion perception, tachometers and speedometers)
- Digital maps and positioning technologies such as GPS, GNSS and GALILEO to accurately determine the vehicle position and construe the surroundings
- Wireless communication technologies to send information back and forth between vehicles and infrastructure

4. MAC Schemes

High mobility of the vehicles and unpredictable driver behavior result in dramatic topologic changes in the network. For this reason, special MAC schemes are needed to manage and answer the issues caused by the characteristics of VANETs. Also, hidden / exposed terminal problems have to be addressed while developing new methods.

Figure 4.1 illustrates the hidden and the exposed terminal problems. *node B* is within the transmission range of both *node A* and *C*; nevertheless *node A* and C are not in each other's transmission range. The *hidden terminal problems* occurs when *node A* and *C* try to send a signal to *node B*. As they cannot hear each other, they would sense the medium idle and may begin to transmit at the same time, which causes a collision at *node B*. Another problem appears when *node B* is transmitting to *node A*. Since *node C* senses the medium busy while node B is accessing the medium, it backs off and cannot transmit to node D even though it would not cause any collision. This is called the *exposed terminal problem*.

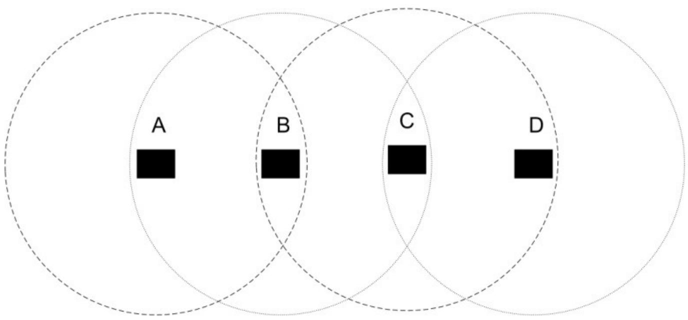

Figure 4.1 Hidden / Exposed Terminal Problems

Below promising candidate protocols which may work efficiently in vehicular ad hoc network are listed:

4.1. ALOHA

ALOHA **[20]** was the first MAC protocol proposed for the creation of single hop packet radio networks. It is based on random access process in which a node may use the channel as soon as a radio packet is ready to be sent. Hence, if two or more neighboring nodes access the channel at the same time, collision occurs. In case of a collision, nodes defer for a random time, and then try to send again. It is assumed that the arrival process of packets follows a Poisson distribution, which leads a maximum throughput of about 18.4% of the channel capacity.

An improvement to ALOHA is slotted ALOHA (S-ALOHA) **[21]**, where the medium is divided into several time slots and any node can transmit only at the beginning of a slot. S-ALOHA halves the vulnerable period of transmission, thus doubles the maximum throughput of the system. Figure 4.2 shows the way nodes access the channel for pure ALOHA and S-ALOHA; shaded packets are lost due to the collision.

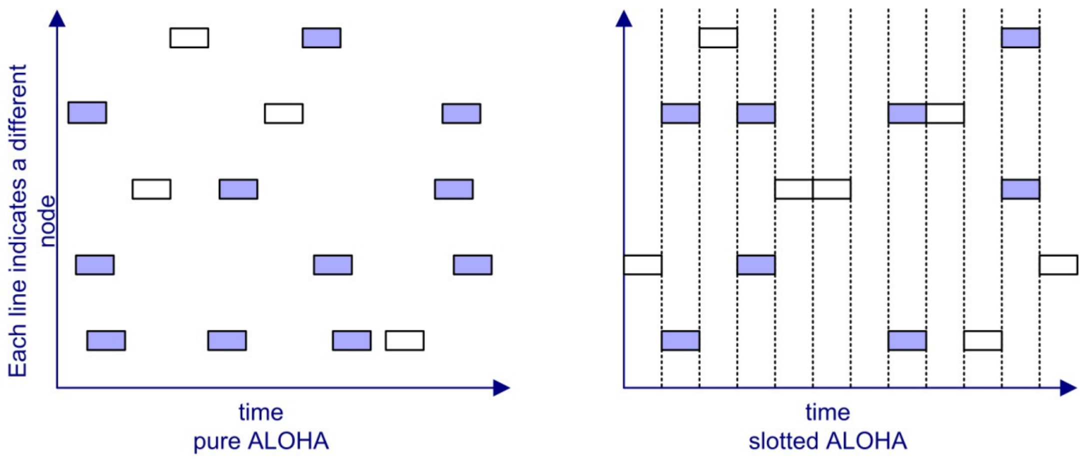

Figure 4.2 ALOHA / s-ALOHA channel access

In **[22]**, the authors propose reservation-ALOHA (R-ALOHA) which is a time slotted medium access scheme where each time slot is assigned to a node by using a reservation method. Borgonovo *et al.* **[23]** improve the performance of R-ALOHA by introducing reliable R-ALOHA (RR-ALOHA) which is able to guarantee a reliable single-hop broadcast communication in a decentralized environment susceptible to the hidden terminal problem. It is designed for the inter-vehicular communication architecture based on UTRA-TDD slotted physical channel.

In RR-ALOHA, a basic channel (BC) composed of one slot per frame is assigned to each node. BC propagates application data as well as service information that guarantees reliable use of the broadcast capability of the channel. Although RR-ALOHA is much the same as R-ALOHA; the former doesn't require a central repeater to get the slot status information. To overcome the hidden terminal problem, each node has to have a global view of the network traffic in a two-hop neighborhood. This is achieved by the Frame Information (FI), a vector with N entries that indicate time slots, which is piggybacked by the packets transmitted in BC beside the payload. When a node is transmitting, FI specifies the status information of the preceding N time slots. If a slot is occupied, the related entry in FI contains the identity of the owner; else it is specified as available. During each frame time, all nodes sense the network activity in their neighborhood.

Upon a successful transmission from a node on some time slot, all the listening nodes mark the identity of that node in the corresponding FI entry. When a node without an assigned BC wants to send, it listens the medium during a full time frame before attempting to transmit and if in the next frame turn the corresponding time slot is marked by its identity in all received FI that time slot is reserved for it in the two-hop neighborhood.

4.2.MACA – MACAW

In [24], the Multiple Access Collision Avoidance (MACA) protocol was proposed. MACA uses two relatively short protocol-specific packets to overcome the hidden and the exposed terminal problem. In this scheme, if a sender node S wants to transmit to a receiver note R, it first sends a RTS (Request to Send) packet to R, indicating the length of the data packet that it wishes to transmit. Upon receiving RTS, R sends back to S a CTS (Clear to Send) packet signaling that it is ready to receive. When S gets CTS, it immediately starts transmission of the actual data packet. In this way, neighbors of both S and R defer for the length of the expected transmission.

Although, RTS-CTS exchange reduces simultaneous access attempts, collisions still occur between RTS packets. Therefore, MACA doesn't always solve the hidden terminal problem. Another flaw of MACA is that, there is no acknowledgment mechanism in the data link layer; that is, in case of a transmission failure retransmission has to be initiated by the transport layer causing significant transmission delay. Bharghavan *et al*. **[25]** extends MACA to MACAW (MACA for Wireless) by adding two more protocol-specific packets, namely data sending (DS) and acknowledgment (ACK). MACAW allows much shorter retransmission times thus a higher throughput comparing to MACA.

4.3.BTMA and DBTMA

A single sharing channel approach has a high probability of causing collisions. To solve this problem, many multi-channel access schemes have been proposed. This approach has the following advantages **[26]:**

- Using more than one channel might increase the throughput since a single channel approach is limited by the bandwidth of that channel
- Packets transmitted on different channels do not interfere with each other, hence number of collisions is significantly decreased
- It is easier to answer QoS requirements.

BTMA (Busy Tone Multiple Access) **[27]** splits the transmission into two channels. A data channel is used to transmit data packets and a control channel is used to transmit a busy tone. When a node wishes to transmit, it first checks the control channel; if it is free, it first transmits a busy tone then the actual data. Immediate neighbors of the sending node also transmit a busy tone, consequently all two-hop neighbors know that the channel is busy and defer. DBTMA (Dual BTMA) **[28]** further improves BTMA by introducing another busy tone: receiver-busy tone. As the name implies, a receiver-busy tone is set up at the receiving end of a transmission. Through the use of transmit-busy tone and receiver-busy tone, DBTMA allows exposed terminals to initiate data communications.

4.4.IEEE 802.11 DCF and IEEE 802.11p

IEEE 802.11 specifies two modes of operation: distributed coordination function (DCF) mode (developed for ad hoc networks) and point coordination function (PCF) mode (developed for centralized infrastructure-based networks) **[29]**. The DCF mode is based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) **[30]**. It may be considered as a combination of CSMA and MACA protocols. Among the usual physical layer sensing, DCF introduces the virtual carrier sensing based on the NAV (Network Allocation Vector). NAV holds a time value indicating the duration for which the medium is expected to be busy. Every node overhearing a transmission updates NAV value (the expected remaining time) by examining the duration time which is added to every packet.

In order to manage the medium access process, time slots are divided into multiple frames and inter frame spacing slots are used.

Before attempting to transmit, each node checks the medium first; if it is sensed busy, it backs off for a certain amount of time. The back off timer value is randomly chosen from the range [0, CW-1] where CW is the contention window in terms of time slots. With every unsuccessful transmission attempt, the width of the CW is doubled. Otherwise, if the medium is sensed idle for a DIFS (DCF inter frame spacing), it sends a RTS packet that carried its identifier and the expected duration time of the transmission. Upon receiving the RTS packet, the receiver node waits for a SIFS (short inter frame spacing) period and then replies with a CTS including also the expected duration time. All neighbors hearing the RTS and CTS packets update their NAV accordingly. When receiving the CTS message, the source node waits for SIFS period and begins the actual data transmission. The destination node waits also for SIFS period before sending an ACK if it receives correctly the data packet. Figure 4.3 demonstrates the transmission timeline in DCF.

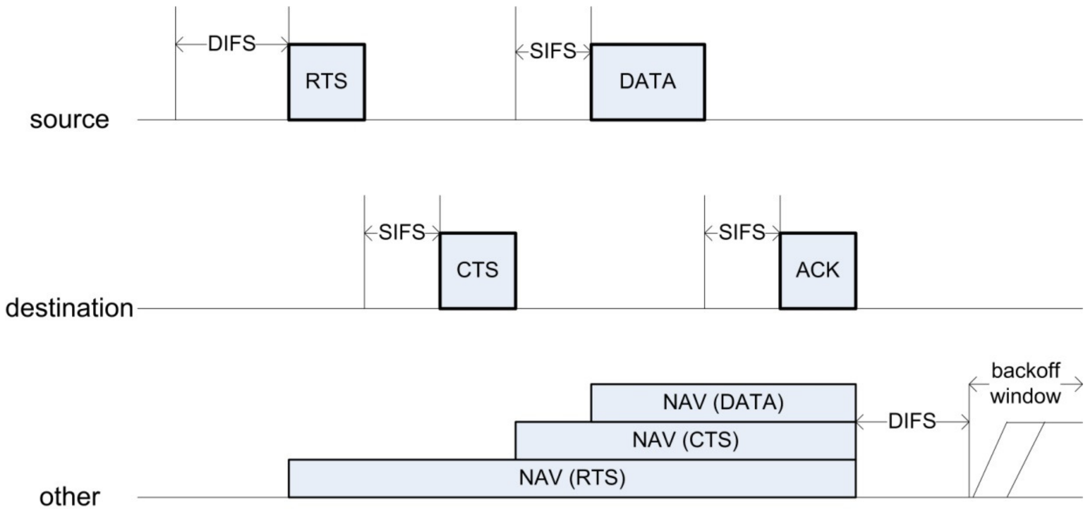

Figure 4.3 IEEE 802.11 DCF Channel Access

IEEE 802.11p also known as WAVE (Wireless Access in the Vehicular Environment) is a new amendment of the 802.11 standard. It specifies improvements to 802.11 to support V2V communications. It addresses reliability and latency issues which are critical requirements in the data exchange between fast-moving vehicles.

5. Cluster Formation for Inter-Vehicle Communications

5.1. Protocol Overview

Clustering formation protocol for IVC (CF-IVC) is based upon the Passive Clustering (PC) model introduced in **[31]**. This model has two main advantages: first, PC does not require any protocol specific packets or signals for clustering purposes. Instead, application-specific data packets piggybacks cluster dependent information in the packet header. Thus, control overhead is drastically reduced. Second, since clusterhead election rule does not need any explicit information exchange between neighboring pairs, the assumption on stationary of vehicles or nodes during the cluster formation phase may be omitted **[32]**.

In addition, CF-IVC divides vehicles into groups according to their speed information (see Table 5.1) and isolates the neighboring vehicles with low relative mobility in the same cluster (Note that the sole exceptions to this rule are gateways, otherwise, it would not be possible to communicate with a vehicle within a different group). Speed information is provided by the global positioning system (GPS) or by the vehicle itself. In any case, every node internally knows the "speed group" which it belongs to prior to cluster formation phase. In this way, the time passed until a cluster member leaves the communication range of its clusterhead is largely extended, so is the life span of the cluster. Consequently, node transition rate between clusters is decreased.

Speed group information is added to the data packet header by the sending node (note that it is not necessary to add clustering group information, as shown in Table 5.1, once the table is set, the relation between speed and clustering groups is static, thus clustering group information is deducible from the speed group information). If a radical speed change occurs and the node moves at a speed out of its clustering group interval during a threshold value *speedT*, it updates its speed / clustering group information and seeks for another cluster to join. Table 5.1 may be an illustration example to denote the relation between speed group and clustering group as a parameter of the vehicle speed in the longitudinal direction.

Table 5.1 Example for Speed / Clustering Group Relationship

Speed interval (km/h)	Speed group	Clustering group
0 - 30	0	0
30 – 45	1	1
45 – 60	2	1
60 – 75	3	2
75 – 90	4	2
90 – 110	5	2
110 – 120	6	3
120+	7	3

At any given moment, a vehicle is in one of the four states: initial (INIT), clusterhead (CH), gateway (GW) or ordinary (ORD). Only nodes labeled as CH or GW are able to forward data packets, in this manner duplicate packet generation is effectively reduced.

5.2.Protocol Details

A. Node Selection

1) Initial State

All vehicles start in initial state and keep their status until they hear from a CH, GW or ORD. Only nodes flagged as INIT are eligible to be CHs, i.e. any two CHs are at least two-hop apart. All cluster-related nodes revert to INIT state if they stay inactive (i.e. no incoming or outgoing traffic) during a period *inactivityT*.

2) Ordinary State

Upon detection of one or multiple CHs, if a node is not qualified to be a GW (see below, gateway selection rules), it changes its state to ORD. Ordinary nodes can only be the source or the destination of communication traffic, that is, they don't relay data packets.

3) Clusterhead Selection

Any node in INIT state is a CH candidate; when they detect a data transmission from a non-CH of the same clustering group or from a GW, one of them claim the CH role and become responsible for relaying intra-cluster packets within its coverage area. Here, "first declaration wins" rule defined in **[31]** applies. In other words, the first INIT node relaying received packet with its CH claim added wins the competition. Any neighboring nodes record the clusterhead information and convert from their INIT state.

4) Gateway Selection

Gateways are the only set of nodes independently chosen of speed information. If it were not for this exception, it is impossible to create a communication route between any pair of different clustering groups. "Hearing from more than one CH" is not a sufficient condition for a node to change its state to GW and it has to be improved for the following reasons:

- to limit the number of gateways: In **[33]** it is shown that if no special criteria are used, almost all non-CH nodes change their state to GW, increasing the number of nodes involving in packet relaying, as well as duplicated packets and the probability of packet collision.

- to maintain network connectivity: Consider that the distance between a gateway and its clusterhead is close to the communication range of the latter, if the gateway moves out of the coverage range the connection might be error prone or lost prematurely.

In traditional clustering schemes, clusterheads keep track of number and location of gateways by the help of protocol specific messages. Naumov *et al*. **[34]** propose "Preferred Group Broadcasting" to restrict the number of rebroadcasting nodes.

Clustering protocol for IVC uses a similar approach to select gateways: if the distance between a CH and a node is between specific values, this node is eligible to become a GW. The distance here is not the actual spatial distance but a value calculated according to the received signal strength. Every clustering group is associated with a RSSI (Received Signal Strength Indicator) interval $I_{CH}= [Li, Hi]$. Because of its high granularity, Cisco's dBm lookup table to convert dBm values to RSSI may be used. This table gives a range of -113 dBm to -10 dBm and the maximum RSSI value is 100.

Upon hearing from CH, a node can compute the signal strength and check whether the resulting value is in the desired interval (see Figure 5.1).

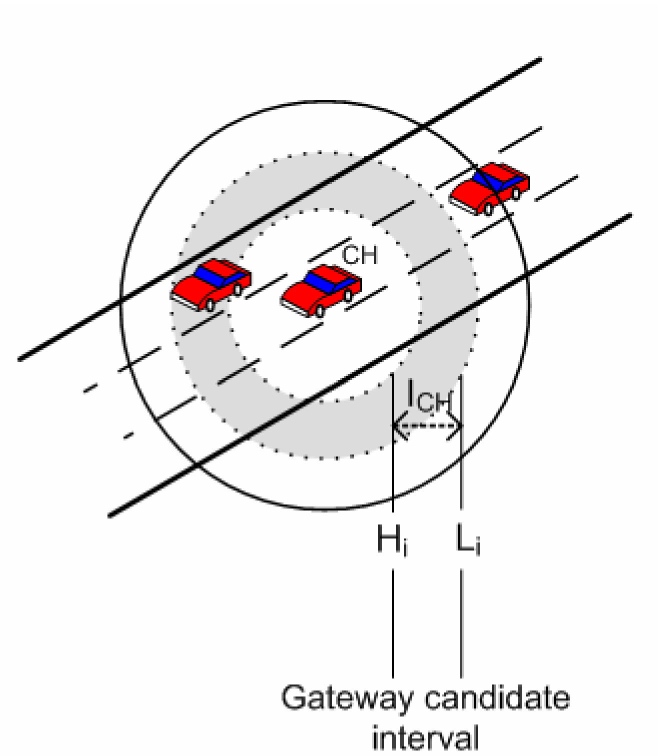

Figure 5.1 Gateway candidate interval of a CH

To compensate high relative speed between CHs and group-independent GWs, the considered strategy may be enhanced by expanding interval I_{CH} according to speed group difference between GW candidate and corresponding CH, as in (4.1)

$$\begin{cases} I_L = L_i - \beta\left|SGrp - CHSGrp\right| \\ I_H = H_i - \beta\left|SGrp - CHSGrp\right| \end{cases} \tag{5.1}$$

where I_L and I_H are two extremities of newly acquired interval I_{GW}, *SGrp* denotes the speed group of GW candidate, *CHSGrp* is the speed group of CH and β denotes the weighting factor.

From the above equation, the larger speed group difference, the larger I_{GW} and $I_{CH}=I_{GW}$ if CH and GW candidate are in the same group.

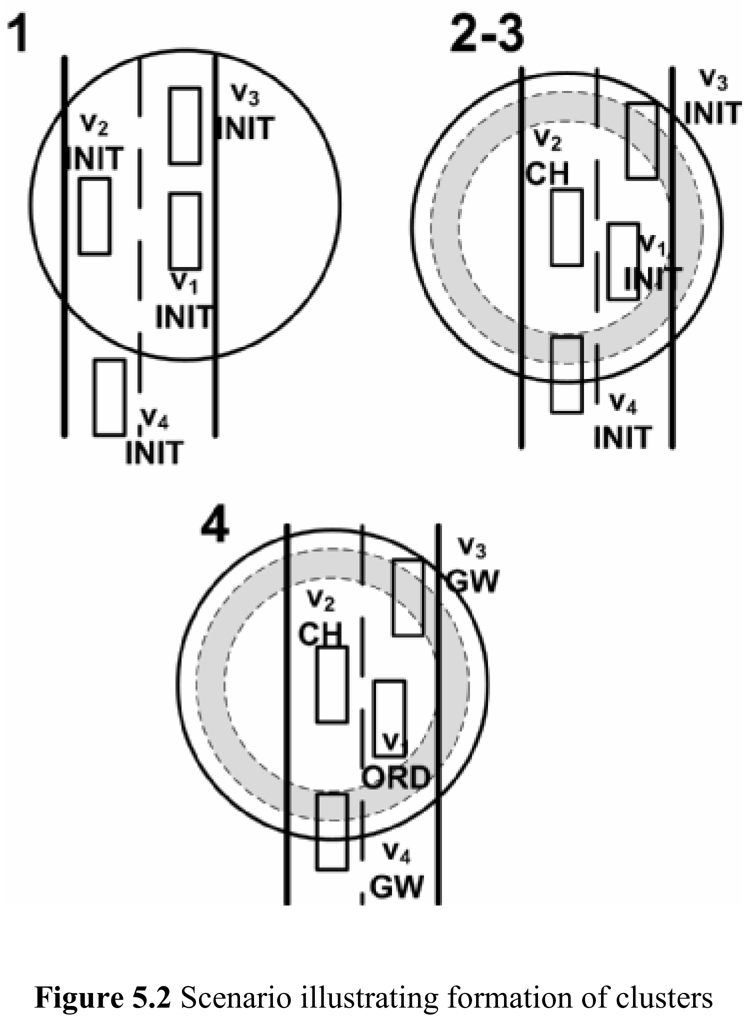

Figure 5.2 Scenario illustrating formation of clusters

A sample scenario is illustrated in Figure 5.2 where all vehicles are in initial state and the first vehicle denoted by *v1* starts communication traffic:

1. When v_1 has a data packet to send, it stamps its group/state information (INIT) to the packet header and sends it.

2. Upon sensing incoming message, v_2 and v_3 check group information and state bits added to header. They detect that packet comes from a non-CH node of the same clustering group. They compete for CH role.

3. v_2 claims it first and wins the competition. It declares its state by changing related bits in the packet header.

4. v_1, v_3 and v_4 "hear" the claim, record the clusterhead information and compute IGW. v_3 and v_4 realize that they are in desired interval and change their states accordingly before relaying the packet. v_1 changes its state to ORD because its RSSI value is not included in I_{GW}.

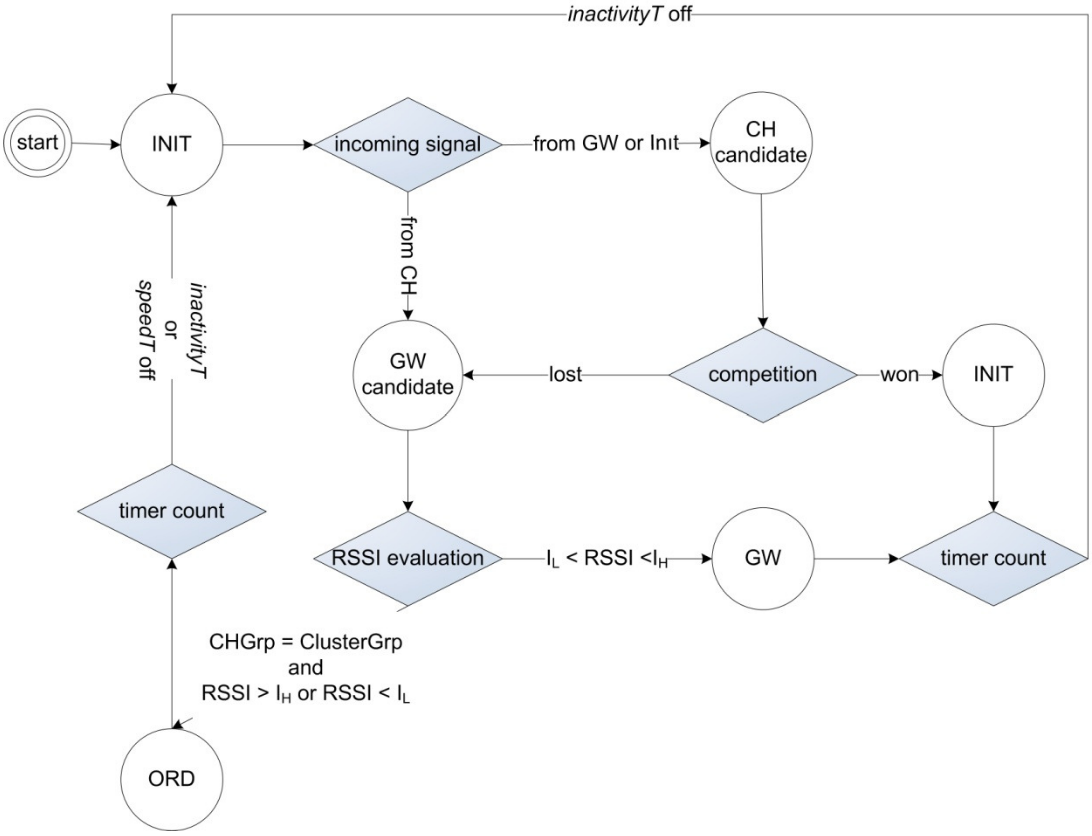

Figure 5.3 Node Selection Mechanism

Notice that the source node does not claim immediately the clusterhead role considering a possible presence of a neighboring CH. If it does not sense a “reply” from a CH during a specific time, it converts to CH itself. Also, there is no delay caused by an additional formation round, i.e. source node sends data packets as soon as they are ready.

Process flow diagram of the presented node selection mechanism is drawn in Figure 5.3.

B. MAC Requirements

In IVC communications, extremely dynamic network topology and latency are issues that should be primarily taken into consideration. Clustering protocol for IVC, presented in the previous chapter, addresses these two by grouping the vehicles with similar speed into same clusters and by effectively reducing protocol specific messages. Nevertheless, this scheme creates overlapping clusters prone to packet collisions and lack of control messages requires lower layer MAC protocols to involve in cluster management.

As nodes in IVC communication network are vehicles, power is not a scarce resource and all hardware requirements may be easily met.

In its coverage area, a CH is responsible for incoming and outgoing packet traffic of its members. Thus, it should regulate medium access by ORD nodes. To increase the frequency reuse and prevent collision, Code Division Multiple Access (CDMA) **[35]**, scheme might be adopted for intra-cluster traffic where the CH behaves as a base station. A small number of orthogonal codes are needed as each cluster is isolated from the rest of the network and the synchronization should only be made locally. On the other hand, for inter-cluster traffic we may use MultiCode Sense CDMA (MCS-CDMA) **[36]** method where all INIT and relaying nodes (CHs and GWs) sense the medium and select their own code from the global set of Pseudonoise (PN) codes available for all the vehicles. Since only specific nodes involve in packet relaying, fewer available PN code is needed than the case where a clustering scheme is not used. Any INIT node releases its acquired PN code and start using the code assigned by its CH once it becomes an ORD.

Table 5.2 Orthogonal Code Assignment

vehicle	state	code via MCS-CDMA	code assigned by CH
v_1	INIT	11111111	--
v_2	INIT	--	--
v_3	INIT	--	--
v_4	INIT	--	--
v_1	INIT	11111111	--
v_2	CH	10101010	--
v_3	INIT	--	--
v_4	INIT	--	--
v_1	ORD	--	10010110
v_2	CH	10101010	--
v_3	GW	11001100	--
v_4	GW	11111111	--

Table 5.2 shows the orthogonal code assignment for the sample scenario depicted in Figure 5.2 in consecutive cluster formation steps. Notice that in step 3, v_4 senses the medium and acquires the free PN code previously released by v_1. Moreover, global set of PN codes is distinct from the set of intra-cluster orthogonal codes which is CH-specific; this way any signal belonging to another intra-cluster traffic is sensed as random noise. Thus, overlapping clusters do not provoke collision.

C. Protocol Improvements

Under normal conditions (during fluent traffic), the majority of vehicles move at the speed of 60-90 kilometers per hour, thus they belong to the 3rd and 4th group. Therefore, if the same static cluster size is chosen, either cluster of populated groups will be overcrowded or the cluster scheme will create isolated islands of vehicles. In the first case, load balance is failed. In the latter case, network coverage is jeopardized.

CF-IVC may overcome this problem by dynamically changing the communication range of CHs according to their speed group.

Even though the majority of vehicles move at the speed of 60-90 km/h, the instantaneous speed of vehicles range from 0 km/h to more than 120 km/h. It is clear that under normal conditions 3rd, 4th and 5th speed groups (i.e. 2nd clustering group) form the most crowded set of vehicles. On the other hand, remaining groups are sparsely distributed along the network. To maintain load balance and network connectivity, CF-IVC may adjust the radio coverage of CHs according to their speed information. In this manner, CFIVC will both implicitly limit the number of nodes per Time cluster and connect sparsely distributed vehicles to the network. One way of managing this without breaking the passive nature of our scheme is to statically assign a value a $(a \leq 1)$ to each of clustering group and make CHs adjust their radio coverage by multiplying a with their maximum signal strength. a is minimum for 2^{nd} clustering group because of its high density and has a higher value for the other groups.

Unfortunately, this technique has a major flaw: it neglects any condition that might affect the maximum speed achievable by vehicles. That is, although vehicles in the first group are rare exceptions when the road traffic is fluent, almost every vehicle moves around 30 km/h during rush hours. For this reason, we propose a slightly different method to be able to dynamically change CHs' radio coverage.

As already mentioned, gateways are the only cluster members allowed to have a clustering group different from the clusterhead's. CHs continuously check its gateways' group information whenever a packet transmission takes place. According to this information, CH updates its maximum perceived speed group (*MPSG*) parameter and starts a timer. If a new *MPSG* is sensed until the timer goes off this new value replaces the older one, or else the following equation applies:

$$MPSG(t+\Delta t) = \left\lfloor \frac{MPSG(t) + CHSGrp}{2} \right\rfloor \tag{5.2}$$

Where *MPSG* is the maximum perceived speed group, *CHSGrp* denotes the clusterhead's current speed group.

By this method, a CH has the sufficient local information about the ongoing traffic in its vicinity. Once *MPSG* value is acquired, CH adjusts its coverage area by simply tuning its transmitter output power as follows:

$$trP = \begin{cases} a_i(trPMax) & \text{if } 4 \leq MPSG \leq 7 \\ a_i(trPMax) - \alpha(7 - MPSG) & \text{otherwise} \end{cases} \tag{5.3}$$

Where a_i is energy coefficient assigned to the i^{th} clustering group, *trP* is transmitter output power (dBm), *trPMax* is maximum power achievable by transmitter (dBm) and α is the weighting factor. Transmitter output power of CHs decreases with the average speed of vehicles, as given by (5.3).
Even though CF-IVC focuses on inter-vehicular communication, roadside message senders / receivers (message relay boxes, beacons etc.) as in **[37]** might be easily included in our scheme if packets generated by these sources are stamped correspondingly. Static code may be assigned to the beacons or repeaters on the road side, and information exchange between vehicular nodes and road side may be achieved directly.

The presented CF-IVC does not need the knowledge of absolute location of their neighbors to form cluster or to communicate. Most of the recent algorithms rely on GPS-based location information to determine relative position between neighboring pairs **[38]** where the loss of GPS signal is a serious matter of concern.

6. Simulation

As an environment, a merge point on a highway section as in Figure 6.1 is selected for the simulation scenario. The highway and the merging road have three and one lane, respectively. The width of each lane is 4 meters and the presented section is 1.2 km in length. Before the actual implementation, simulation development tools used for implementing out scenario are presented:

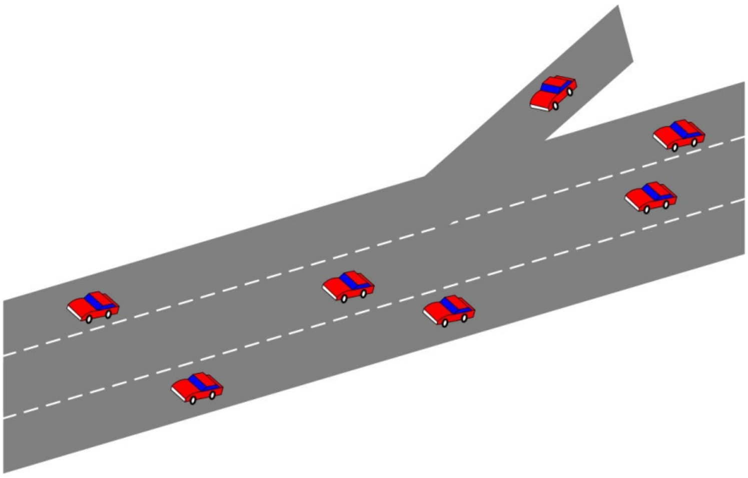

Figure 6.1 Simulation Scenario

6.1.OMNeT++

OMNeT++ **[39]** is a C++-based discrete event simulation environment developed for simulating computer networks and various distributed systems. It supports the modeling of very large networks built from reusable model components. OMNeT++ is open-source and available on UNIX systems and on Windows under the GNU General Public License. It was made public in September 1997 and since then it has gained a fairly large user community thanks to its capability to fill the gap between research oriented open-source simulation environments and expensive commercial alternatives.

A. OMNeT++ models

OMNeT++ models are composed of one or more modules that communicate with *message passing*. *Simple modules*, being the active units, are written in C++ language, using the simulation library. If necessary, they may be grouped into *compound modules*. For the sake of transparency, both kind of modules are instances of module types and can be created as building blocks without any distinction.

Messages are usually sent via *gates*, the input and output interfaces of modules. Input and output gates can be linked with connections that may have assigned properties such as propagation delay, BER or data rate.

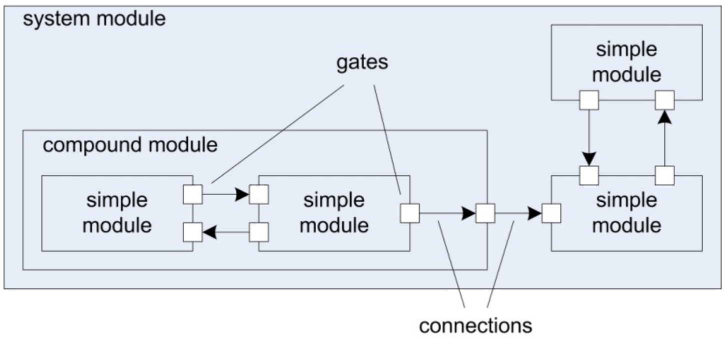

Figure 6.2 OMNeT++ Model Structure

Modules may also have *parameters* to pass configuration data to simple modules and to define model topology. Parameters can be passed *by value* or *by reference*.

B. NED Language

NED is a topology description language used to define the structure of the model. Files containing network descriptions have a `.ned` suffix. OMNeT++ includes a graphical editor which uses NED as its native file format, thus users can edit their desired topology either graphically or in NED source view.

A network description in NED can contain the following components:

- Import directives
- Channel definitions
- Simple and compound module definitions
- Network definitions

Import directives are used to import declarations from a previously written description file. Channel definitions specify a connection type of given characteristics. Simple modules are defined by declaring its parameters and gates. Compound modules have additional sections: submodules and connections. Submodules are the building blocks of a compound module, they are either simple or compound themselves. Connections state explicitly how the gates of the compound module and its immediate submodules are connected; a particular gate may only be used in one connection. Networks definitions specify the actual simulation model that can be run, which is an instance of an already defined module type. Only module types without gates can be used in a network definition.

NED files can be dynamically loaded into simulation programs and they contain declarative blocks which allow parameterizing topologies, in that way dynamic model topologies can be designed instead of fixed ones.

C. OMNeT++ Programming Model

Simple modules are programmed in C++ using the OMNeT++ class library. They are the atomic elements in module hierarchy, that is, they cannot be divided any further. The behavior of the model is implemented by extending `cSimpleModule` class, which is derived from a common base class, `cModule`.

When adding functionality to their simple modules, users have to redefine following virtual member methods provided by `cSimpleModule`:

- void `initialize`( )
- void `handleMessage`(`cMessage` *`msg`)

- void activity ( )
- void finish ( )

When initialize ( ) method is called, OMNeT++ builds the network by creating simple / compound modules and connections between them according to the corresponding .ned file. It means that OMNeT++ calls the initialize () methods of all modules at the beginning of a simulation. If the simulation is completed successfully, finish ( ) is usually called to save scalar results into an external file.

Model behavior is added by implementing handleMessage (*msg) or activity ( ) methods. They are implemented by adopting completely different programming models, for that reason exactly one of these methods has to be redefined in a module definition.

handleMessage (*msg) is called whenever a message arrives at the module. The simulation kernel does not distinguish between messages and events, which means that events are represented as scheduled self-messages. Messages can be sent via output gates or directly. Upon receiving a message, handleMessage (*msg) has to return immediately after processing it. As its explication implies, handleMessage (*msg) is an event-processing function. On the other hand activity is a co-routine; that is, it runs in its own thread (cooperative multitasking); users may switch between co-routines without losing their states. activity ( ) typically contains an infinite loop and never return; i.e. when it exits the module is terminated.

Although co-routine based programming is a natural approach, modules implementing activity ( ) do not scale well since every thread has its own CPU stack. Moreover, runtime overhead caused while switching between co-routines is much larger than the case where simple function calls are used. Consequently, in most situations handleMessage (*msg) should be preferred to activity ( ).

6.2.Mobility Framework

Mobility Framework (MF) **[40]** is a mobility extension for OMNeT++ written by the Telecommunication Networks Group at the Technische Universitaet Berlin. It is designed to support node mobility, dynamic connection management and a wireless channel model. Thus, the framework can be used for the simulation of the following types of networks:

- fixed wireless networks
- mobile wireless networks
- distributed and centralized networks
- sensor networks
- multichannel wireless networks

Users can implement their own simulations by extending the *basic module* classes provided by the framework without dealing with the interoperability and the interfacing issues.

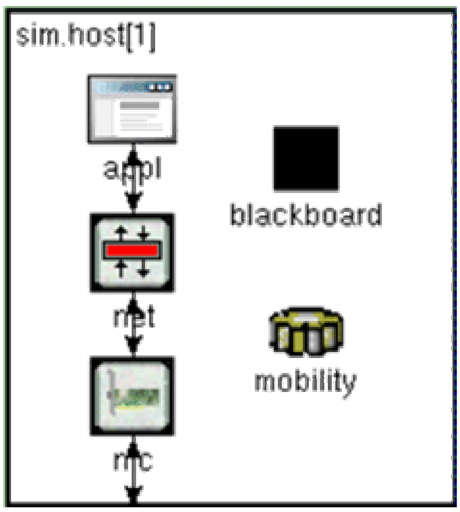

Figure 6.3 Internal Structure of a Mobile Node

Figure 6.3 shows the internal structure of a mobile host. Message-processing takes place at different levels in a layered architecture as in TCP/IP model. *Mobility* module handles the movement of the host and the *blackboard* module provides the necessary means for information sharing between layers. The relevant information could vary from energy status to received radio power.

In MF, the protocol functionality is added by implementing `handle*Msg` ( ) functions; they contain all necessary processing and forwarding information. `handleSelfMsg`() is used to simulate all timer related events, `handleUpperMsg`( ) and `handleLowerMsg`() is called when a message arrives from the upper layer and vice versa.

Message packets created by users have to extend one of the basic message classes and to have fixed formats to provide encapsulating / decapsulating functionality. Encapsulation means enclosing a lower layer message by adding necessary header information, the message is then encapsulated before being forwarded to the upper layer. Users have to overwrite `encapsMsg` ( ) / `decapsMsg` ( ) functions when using their own message packets. A control information class can be used to add meta information to a message, this information is only relevant for the next processing layer. For example, `NetwControlInfo` is utilized by network layer to pass the networks address to the application layer.

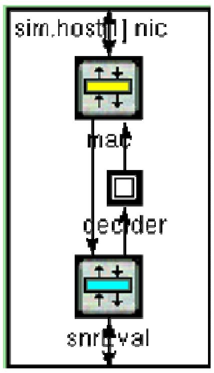

Figure 6.4 Physical Layer in MF

The physical layer is divided into `SnrEval` and `Decider` submodule; in brief, `SnrEval` is responsible for SNR calculation and Decider evaluates the obtained results to define bit errors. `SnrEval` also simulates transmission delay for received messages and store SNR information in a `SnrList`. As Figure 6.4 depicts, `Decider` module process only messages coming from the lower layer, message coming from the medium access layer bypass this module because only messages coming from the channel may be assigned with bit errors.

The `Blackboard` module offers the methodology to publish internal state changes of the protocol, monitors obtain the desired info by subscribing to these values. Moreover, `Blackboard` module allows the information exchange without passing parameters. The subscription takes place in initialization function in stage 0 (it has been already mentioned that OMNeT++ supports multi-initialization) and publishers initialize the state parameters in stage 1. This way, all subscribers may properly set a starting value for their copies.

Mobility is dealt with locally in each `Host` module. The `ChannelControl` module establishes connections between mobile hosts based on the location changes advertised by a mobility module. It determines the maximum interference distance as well by examining global network parameters. New mobility models can be implemented by deriving mobility modules (`CircleMobility`, `LinearMobility` etc.) that come with MF.

6.3.Implementation and Results

A. Simulation Setup

In programming phase, the following list was taken into account during simulation implementation:

- For the network layer, process flow illustrated in fig. 4.3 is implemented.
- Packets arrive from application layer following a Poisson distribution with a variable average number.

- Concerning the propagation of radio waves, Rayleigh fading model is adopted.
- The medium access is based on IEEE 802.11 wireless LAN standard.
- The maximum data rate is 11 Mbps.
- The maximum transmitter power is 110 mW.
- Fixed thermal noise value is -110 dBm.
- Sensitivity threshold is -119.5 dBm.
- Lower bound for being a gateway candidate (iGwL) is -106.6 dBm and upper bound (iGwH) is -102.6 dBm.
- Nodes change their state back to INIT if no communication traffic is sensed for 6 seconds.
- CH candidates wait for a random period of time between 0.001 and 0.01 seconds before claiming the role.
- Each network packet has a fixed size of 256 bytes.
- Simulation duration cannot exceed 5000 seconds.
- Beside the source / destination network addresses the network packet header contains two more fields (of 2 and 3 bits) indicating the cluster related state and the speed group of the node.
- Simulation runs for 50 nodes.
- At the beginning, each node is at its initial state (INIT).

B. Simulation Results

For the evaluation, node distribution, the average number of nodes per cluster and the number of packets sent/dropped/relayed for each type of nodes are examined. Following diagrams show obtained results:

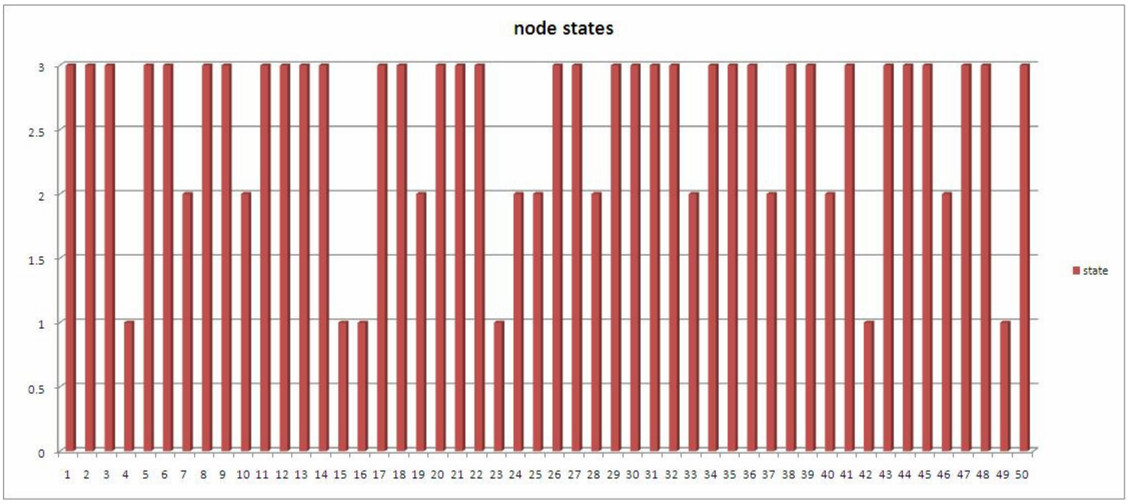

Figure 6.5 Node States

Figure 6.5 shows the cluster-related state of each node when the simulation is terminated. Integers 0 to 3 are assigned to each state (INIT, CH, GW and ORD respectively) for easier data collection.

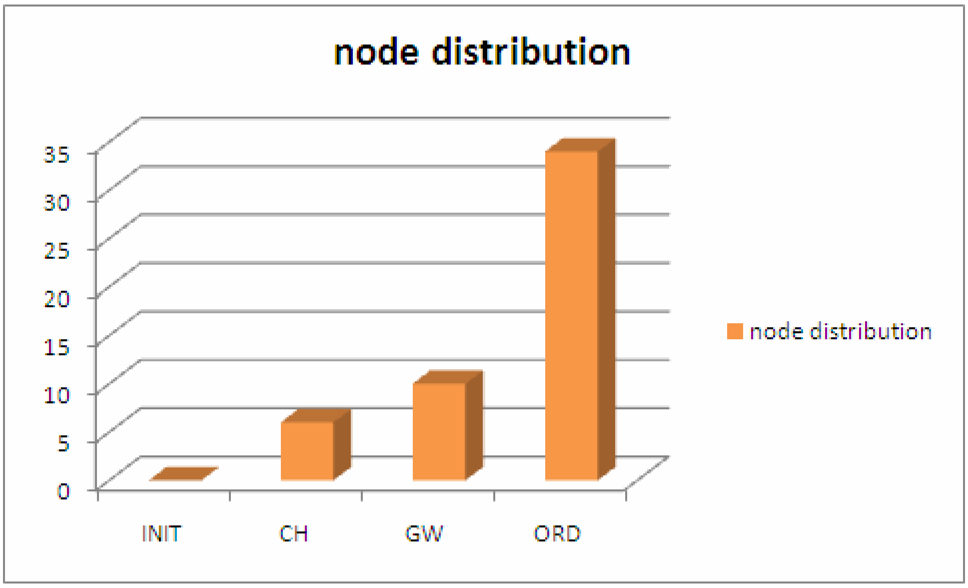

Figure 6.6 Node Distribution

Figure 6.6 clearly depicts that each node switched to a member state (no INIT), ORD nodes being abundant.

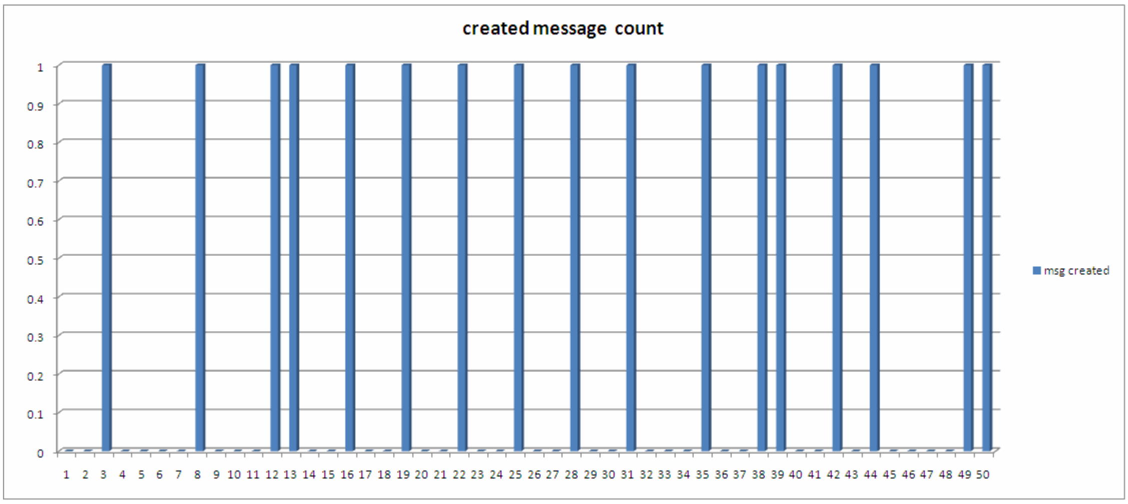

Figure 6.7 Created Message Count

Number of messages created at the application layer by each node is represented by figure 6.7.

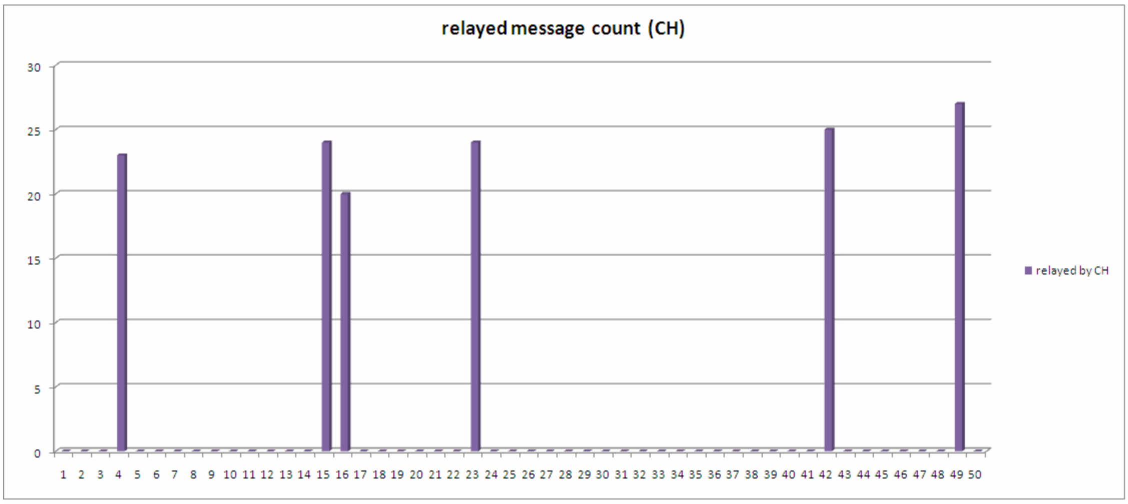

Figure 6.8 Relayed Message Count (CH)

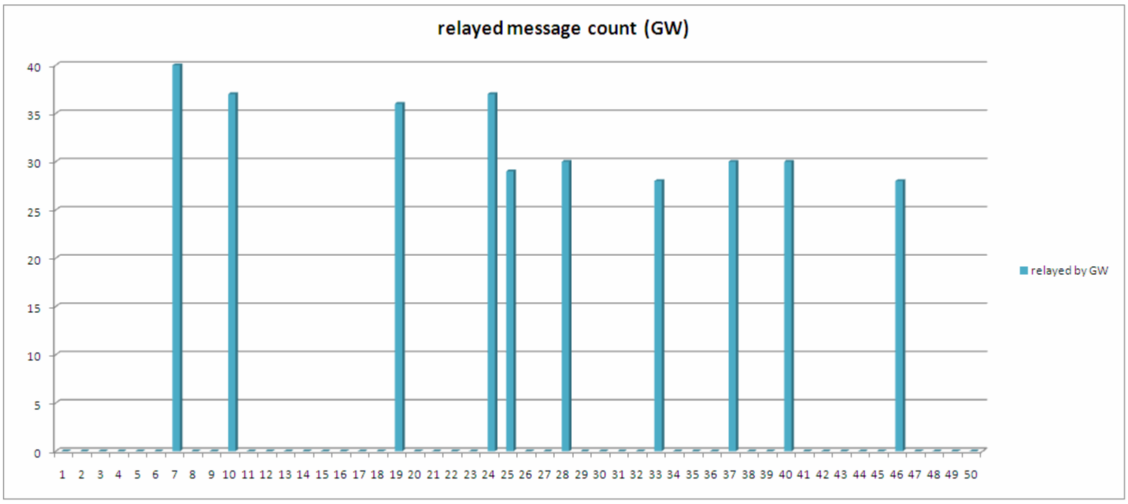

Figure 6.9 Relayed Message Count (GW)

Figure 6.8 and figure 6.9 show the number of relayed packets by CHs and GWs, respectively. Relaying nodes at the extremities of the networks have fairly smaller counts than the others.

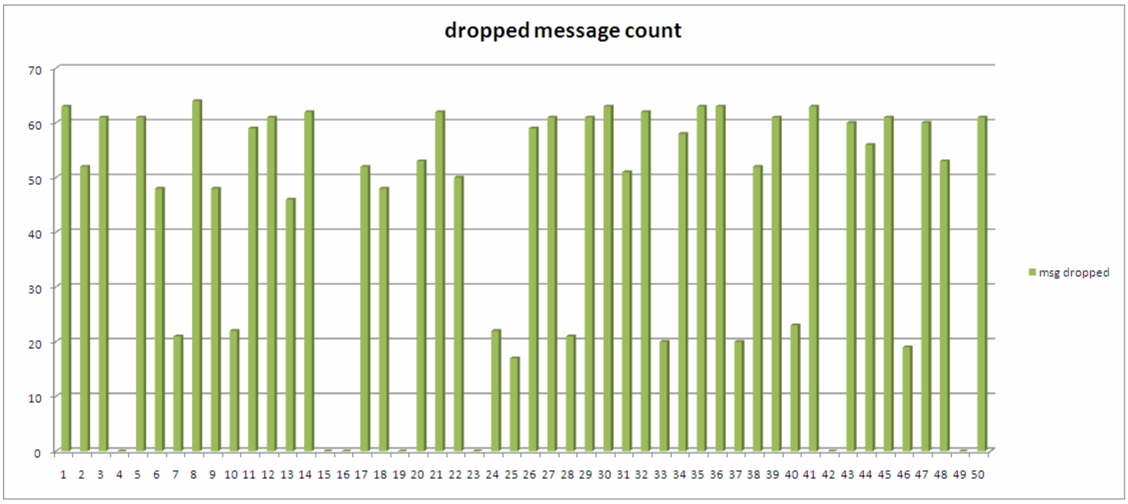

Figure 6.10 Dropped Message Count

As indicated in figure 6.10, ordinary nodes drop any packet unless incoming packet is relayed by their CHs and they are the final destination. Gateways, on the other hand, relay inter-cluster packets but do not intervene in one-hop intra-cluster traffic.

7. Conclusion

Although the underlying technology is not mature enough, VANET is a promising technology for intelligent transportation system. Recent advancements in the area clearly show that vehicles could benefit from wireless communications in a near future. Many academic and private initiatives have been started all around the world to overcome the open research challenges that need to be addressed in order to complete the standardization process. Beside the technological issues, it is also imperative that certain market penetration be reached before the deployed applications become fully functional.

Concerning the communication stack, it is shown that in physical layer the spectrum allocation issue is nearly solved and a certain degree of world-wide harmonization is possible. However, MAC architectures proposed so far are proven to work well only in limited scenarios; their performances degrade quickly when networks load and mobility is increased. In the network layer, geocasting and trajectory-based scheme seem more promising than the other routing protocols. Nevertheless, in VANETs node density depends heavily on the driving environment and the time of the day; as a result finding a universal routing solution for all VANET application is extremely hard.

In this thesis, CF-IVC was presented. It is a hierarchical inter-vehicle communication scheme that improves network efficiency by dividing nodes in smaller and more manageable groups. Thus, medium access is controlled without the intervention of a global central authority and end-to-end communication routes are virtually formed without extra overhead. The nodes are assigned by specific tasks autonomously according to their speed information. Once the cluster is formed appropriate orthogonal codes are assigned to the nodes, assuring collision-free data exchange among communication pairs.

The simulation results show that the average number of nodes per cluster is 8.33, which is more than acceptable for an easier local management. From that, one can conclude that CF-IVC scales well. At the end of the simulation, no INIT node is observed, in other words all of the nodes claim a cluster-specific role, which proves the strong network connectivity achieved by CF-IVC. Furthermore, dynamic transmission range provides adaptability for various scenarios. Beside the connectivity and management issues, CF-IVC increases overall throughput; according to simulation results, the number of relaying nodes is effectively reduced by 68%, thus unnecessarily repeated messages are averted. Consequently, network traffic is improved by 81.5% vis-à-vis traditional flooding schemes.

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His two papers (co-author Tankut Acarman), "Clustering Approach to Vehicle-to-Vehicle Communication Application" and "Cluster Formation for Inter-Vehicle Communication" were published in proceedings of V2VCOM 2007 and ITSC 2007, respectively.