THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

On Medium Access Control for Vehicular Communication over Device-to-Device Links: Radio Resource Management and Network Synchronization

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To my parents and Wei

Abstract

Recent progress in wireless communication technologies along with the development in automotive industry bring new potentials to improve traffic safety, efficiency, and comfort. The enhancement can be achieved by vehicle-to-everything (V2X) communications that enable vehicles to cooperate with other vehicles, devices, and infrastructures. Due to the limitations of the current solutions for vehicular applications, integrating direct device-to-device (D2D) links into cellular systems is deemed a promising technology for V2X communications. However, the investigation of D2D-based V2X communication is still at its infancy and many issues, especially on medium access control (MAC) layer, need to be addressed before its efficient deployment. The aim of the thesis is to motivate the use of direct D2D links in cellular systems for supporting safety-related vehicular communications and to study two important MAC layer issues in this regard: radio resource management (RRM) and network synchronization.

In the first part of the thesis, we first give an overview of vehicular communications including its legacy solutions and some future potentials. Then, we motivate the promising usage of D2D links for supporting V2X communications and investigate at a high level the MAC layer in this context, where generally speaking, MAC mechanisms decide how several transmitters share a common medium. Moreover, depending on different coverage scenarios, we distinguish between two MAC modes for D2D-based V2X communication and accordingly present two research questions, which are then studied from various aspects in detail. More specifically, when communicating vehicles are in network coverage, the base station (BS) can coordinate transmissions in a centralized approach, which is referred to as the network scheduled MAC mode. In this case, to mitigate the interference resulting from resource reuse between conventional cellular users (C-UEs) and vehicular users (V-UEs) as well as to satisfy the stringent requirements of vehicular applications, RRM is a key design issue. On the other hand, when some of, or all of, the communicating vehicles are out of network coverage, V-UEs can select the resource to transmit in an autonomous manner, which is referred to as the autonomous MAC mode. In this case, network synchronization is a crucial enabler to implement efficient time-division MAC methods.

The second part of the thesis includes six appended papers that investigate the two above research questions specifically.

In [Paper A], under the assumption that different V-UEs use orthogonal resource blocks (RBs) among each other, we study an RRM problem for D2D-based V2V communications with strict latency and reliability requirements and with access only to slowly time-varying channel state information. Even though the orthogonality among V-UEs brings simplicity to RRM design, allowing multiple V2X transmissions on the same RB will not only improve spectrum efficiency, but also lead to potentially less interference to C-UEs due to spatial reuse. Therefore, with dispensed orthogonality assumption, [Paper B] and [Paper C] formulate an RRM problem and solve it through two algorithms that are driven by different theoretical tools. Furthermore, by capturing the distinct requirements as well as potentials of V-UEs and conventional C-UEs, a novel RRM framework is presented in [Paper D] to enable vehicle networks in 5G cellular systems.

In addition, network synchronization for autonomous D2D-based V2X mode is studied in [Paper E] and [Paper F]. More specifically, assuming all the communicating devices (including our target application vehicles as special cases) are out of network coverage, we in [Paper E] study the synchronization problem to achieve an internal consensus on clock values without relying on a network hierarchy. Moreover, in [Paper F], we investigate a practical synchronization scenario in D2D networks without knowing the coverage status. In particular, main challenges and problem formulations are detailed for the synchronization problem in this situation and then a synchronization algorithm as well as the underlying theories are presented accordingly.

Keywords: 3GPP LTE, autonomous D2D, channel state information, combinatorial optimization, consensus, convex optimization, device-to-device (D2D), IEEE 802.11p, matching theory, medium access control (MAC), network controlled D2D, network synchronization, Perron-Frobenius theory, radio resource management (RRM), recursive estimation, traffic safety, vehicle-to-everything (V2X) communications.

List of Included Publications

The thesis is based on the following appended papers:

[Paper A] W. Sun, E. G. Ström, F. Brännström, K. C. Sou, and Y. Sui, "Radio resource management for D2D-based V2V communication," *IEEE Trans. Vehicular Technol.*, to appear.

[Paper B] W. Sun, D. Yuan, E. G. Ström, and F. Brännström, "Resource sharing and power allocation for D2D-based safety-critical V2X communications," in *Proc. IEEE International Conference on Communications (ICC) Workshop*, London, UK, June 2015.

[Paper C] W. Sun, D. Yuan, E. G. Ström, and F. Brännström, "Cluster-based radio resource management for D2D-supported safety-critical V2X communications," *IEEE Trans. Wireless Commun.*, vol. 15, no. 4, pp. 2756–2769, Dec. 2015.

[Paper D] W. Sun, M. Botsov, E. G. Ström, F. Brännström, and L. Yan "A novel framework for radio resource management in 5G enabled vehicular networks," to be submitted to *IEEE Trans. Commun.*

[Paper E] W. Sun, E. G. Ström, F. Brännström, and M. R. Gholami, "Random broadcast based distributed consensus clock synchronization for mobile networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 6, pp. 3378–3389, June 2015.

[Paper F] W. Sun, F. Brännström, and E. G. Ström, "Network synchronization for mobile device-to-device systems," submitted to *IEEE Trans. Commun.*

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Gothenburg, June 2016

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Acronyms

The following acronyms are used in the first part of the thesis.

3GPP:	3rd Generation Partnership Project
5G:	Fifth Generation
ADMM:	Alternating Direction Multiplier Method
AIS:	Automatic Identification System
ARES:	Adaptive distRibuted nEtwork Synchronization
APP layer:	APPlication layer
BS:	Base Station
BSS:	Basic Service Set
C-ITS:	Cooperative Intelligent Transportation Systems
C-UE:	Cellular User Equipment
CEN:	European Committee for Standardization
CROWN:	Cluster-based Resource block sharing and pOWer allocatioN
CSI:	Channel State Information
CSMA/CA:	Carrier Sense Multiple Access with Collision Avoidance
D-UE:	Device-to-device User Equipment
D2D:	Device-to-Device
DCC:	Decentralized Congestion Control
DL:	Downlink
EDCA:	Enhanced Distributed Channel Access
ETSI:	European Telecommunications Standards Institute
FCC:	Federal Communications Commission
FTSP:	Flooding Time Synchronization Protocol
GPS:	Global Positioning System
IEEE:	Institute of Electrical and Electronics Engineers
LTE:	Long-Term Evolution
LTE-A:	Long-Term Evolution-Advanced

MAC:	Medium Access Control
MME:	Mobility Management Entity
MWM:	Maximum Weight Matching
OCB:	Outside the Context of a Basic service set
OFDM:	Orthogonal Frequency-Division Multiplexing
OFDMA:	Orthogonal Frequency-Division Multiple Access
PHY layer:	PHYsical layer
ppm:	parts per million
PPS:	Pulse Per Second
QoS:	Quality of Service
RAN:	Radio Access Network
RB:	Resource Block
RBDS:	Random Broadcast based Distributed consensus clock Synchronization
RBSPA:	RB Sharing and Power Allocation
RRM:	Radio Resource Management
S-GW:	Serving Gateway
SC-FDMA:	Single-Carrier Frequency-Division Multiple Access
SINR:	Signal to Interference plus Noise Ratio
SOLEN:	Separate resOurce bLock and powEr allocatioN
SR:	Synchronization Round
STDMA:	Self-organized Time Division Multiple Access
TC:	Technical Committee
TDP:	Time Diffusion synchronization Protocol
TPSN:	Timing-sync Protocol for Sensor Networks
TSF:	Timing Synchronization Function
UE:	User Equipment
UL:	Uplink
V-UE:	Vehicular User Equipment
V2I/N:	Vehicle-to-Infrastructure/Network
V2P:	Vehicle-to-Pedestrian
V2V:	Vehicle-to-Vehicle
V2X:	Vehicle-to-everything
VANET:	Vehicular Ad Hoc Network
WAVE:	Wireless Access in Vehicular Environment

Contents

Part I

Introductory Chapters

Chapter 1

Overview of Cooperative Intelligent Transportation Systems

The rapid advances in wireless communication technologies along with the growing number of vehicles being equipped with wireless devices have brought new potentials to automotive industry. These technologies allow vehicles to communicate their position, speed, steering-wheel position, and other data to other vehicles and entities. The various types of information can be further exploited to improve road safety, traffic efficiency, and other non-safety services such as comfort and infotainment.

In this context, cooperative intelligent transportation systems (C-ITS) refer to a set of communication technologies to enable the cooperation of vehicles, network infrastructures, pedestrians, and so on. Applications driven by C-ITS rely on several types of communications [1]:

- vehicle-to-vehicle (V2V): the communication between vehicles;
- vehicle-to-pedestrian (V2P): the communication between a vehicle and a device carried by an individual (e.g., handheld terminal carried by a pedestrian, cyclist, driver or passenger);
- vehicle-to-infrastructure/network (V2I/N): the communication between a vehicle and a road side unit or a network centralized controller.

To harmonize all these types of vehicular communications, the term vehicle-to-everything (V2X) has been proposed.

In what follows, we describe the current legacy solutions of V2X communication and discuss their respective pros and cons. Based on the discussions, a promising technology is then promoted for future C-ITS.

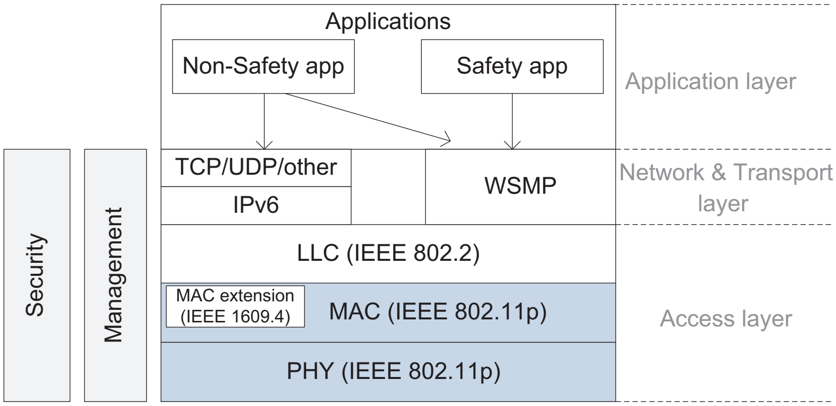

Figure 1.1: IEEE WAVE architecture.

1.1 Today's C-ITS

Two major standardized technologies are currently considered for wireless access in V2X communications: short-range ad hoc communication technology via the Institute of Electrical and Electronics Engineers (IEEE) 802.11p[1] standard [3] and cellular network via the 3rd Generation Partnership Project (3GPP) Long-Term Evolution (LTE) standard. In this section, we briefly introduce these two standards along with their associated architectures and summarize their pros and cons when being applied to V2X communications.

1.1.1 Vehicular Ad Hoc Network

To adapt to the rapid change of network topologies and the local nature of C-ITS services, vehicular ad hoc network (VANET) has been widely considered as the approach to enable V2X communications. In this regard, large amounts of efforts have been made to the research and standardization process. Comprehensive surveys are presented in [4, 5].

Probably, the most notable architectures developed along this direction are the U.S. IEEE wireless access in vehicular environment (WAVE) and the European Telecommunications Standards Institute (ETSI) Technical Committee (TC) ITS. In U.S., the Federal Communications Commission (FCC) has allocated 75 MHz bandwidth over the 5.850–5.925 GHz spectrum range for C-ITS applications. The overall bandwidth is subdivided into seven channels with 10 MHz for each one. On the other hand, in Europe, 50 MHz channel bandwidth in the range of 5.875–5.925 GHz, containing five 10 MHz channels, is dedicated to C-ITS [6].

The WAVE protocol stack is shown in Fig. 1.1, which includes IEEE 802.11p for lower layers, i.e., physical (PHY) layer and medium access control (MAC) layer, and

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[1] IEEE 802.11p has been classified as superseded and integrated into IEEE 802.11-2012 [2]. Nevertheless, for simplicity, we refer to IEEE 802.11p throughout the thesis.

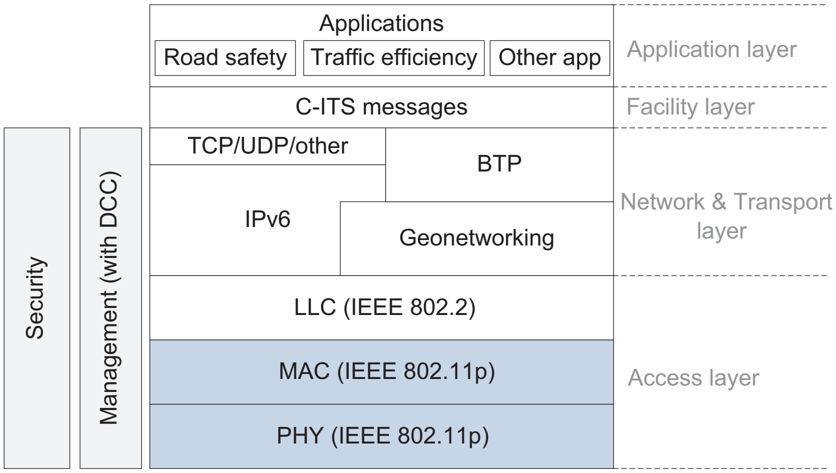

Figure 1.2: ETSI TC ITS (current) architecture.

IEEE 1609 for higher layers. Moreover, in Europe, ETSI and European Committee for Standardization (CEN) are in charge of developing the standards for C-ITS, where the current reference architecture is depicted in Fig. 1.2. Compared to WAVE, the European protocol stack involves a facility layer situated in-between the network & transport and application layers. More details about the two architectures and the standardization process on C-ITS can be found in [6–9].

As seen from Fig. 1.1 and Fig. 1.2, the stacks and the associated standards from U.S. and Europe are not harmonized. In fact, however, the difference between the two reference architectures mainly lies in higher layers, while the lower layers are almost identical with the exception of multi-channel operations. More specifically, the channelization in WAVE is specified in IEEE 1609.4, whereas the use of multiple frequency channels in Europe is supported by the decentralized congestion control (DCC) mechanism integrated in the management module. Concerning PHY layer and MAC layer, both architectures are based on the IEEE 802.11p [3] that was initially approved as an amendment of 802.11 to cope with highly mobile wireless environments and to satisfy various ITS applications. Note that in Europe, the standard of access technology is referred to as ETSI ITS-G5, which is a European profile of IEEE 802.11p [6].

The PHY layer of IEEE 802.11p uses orthogonal frequency division multiplexing (OFDM) with 64 subcarriers (48 for data, 4 for pilot, and 12 for null). Additionally, it uses 10 MHz channel spacing instead of 20 MHz to better cope with the delay spread. The MAC layer of 802.11p adopts the enhanced distributed channel access (EDCA) mechanism which inherits the carrier sense multiple access with collision avoidance (CSMA/CA) and extends it by providing different channel access parameters in order to achieve service prioritization. More importantly, compared to 802.11a, the main innovation of 802.11p is that it applies a default ad hoc mode referred to as Outside the Context of a Basic Service Set (OCB). In the OCB operation mode, the process of authentication and association for establishing a Basic Service Set (BSS) is avoided, and therefore the setup procedure is simplified which nicely fits the safety applications with short-lived connectivity and low-latency requirement.

IEEE 802.11p is the currently recognized standard for C-ITS applications due to its desirable features of easy deployment, low cost, and native support of V2X communications in ad hoc mode. Regarding day-one C-ITS applications including both V2V and V2I exchange of basic safety messages (e.g., hazardous location and road works warnings), there is a consensus that 802.11 will just meet the application requirements [10]. However, it is also admitted that relying only on the 802.11p will become problematic when more vehicles are equipped with wireless devices and an increased number of C-ITS applications appear with stringent requirements [10, 11].

The main drawbacks of the 802.11p technology come from scalability and difficulties in providing quality of service (QoS). The scalability issue is caused by the CSMA method at the MAC layer which follows a listen-before-transmit principle. More specifically, each vehicle first senses the channel during a predetermined listening period. If the channel is perceived as idle, the vehicle will start to transmit; otherwise, the vehicle will perform a backoff procedure, i.e., it will defer its access for a randomized time period within a contention window. This way, the performance of CSMA will deteriorate seriously with increased network load due to the contention-based nature. This is sometimes referred to as channel congestion problem. Furthermore, the lack of pervasive infrastructure deployment makes the 802.11p standard be normally considered to offer intermittent connectivity among vehicles and devices. Therefore, the strict latency and reliability requirements of future safety-related C-ITS applications can hardy be fulfilled.

1.1.2 Cellular-Based Vehicular Network

The two aforementioned concerns of 802.11p are due to the lack of a centralized coordinator. Additionally, the third hurdle towards the realization of V2X communications based on 802.11p is its low market penetration. In fact, the deployment of ad hoc networks suffers from the typical chicken-and-egg problem, since a certain number of 802.11p equipped vehicles is required before the approach becomes effective. Alternatively, cellular network technologies have recently attracted more and more interests for C-ITS services. Among them, the 3GPP LTE (Release 8) is of particular interest since it provides both high data rate and (relatively) low latency, in addition to the common merits of cellular systems such as wide coverage, high market penetration, and high-speed terminal support. Throughout the whole thesis, when we say LTE we mean LTE Release 8, unless otherwise specified. It is worth mentioning that direct communications between user equipments (UEs) were not supported in LTE Release 8. However, the direct D2D communications have been introduced since LTE Release 12.

The overall LTE system is characterized by a flat all-IP architecture with a reduced number of network entities and a separation of the control plane and user plane traffic. Thanks to the flat architecture, LTE can provide round trip times theoretically lower than 10 ms, and idle to active latency of up to 100 ms. The radio access network in LTE

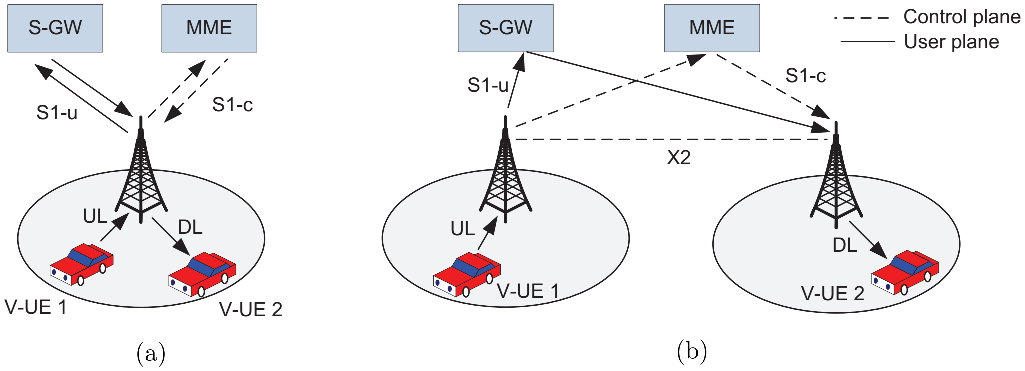

Figure 1.3: UE communication through LTE architecture. (a) Served by the same BS. (b) Served by different BSs.

is composed of base stations (BSs) which are responsible for all radio-related functions[2]. Detailed descriptions of LTE architecture can be found in [12, Chapter 8].

In a traditional LTE network, the UEs need to connect to a BS to be able to transmit. Fig. 1.3 depicts two examples of vehicular UE (V-UE) 1 transmitting data to V-UE 2 through an LTE architecture, where the two V-UEs are served by the same BS in Fig. 1.3(a) and different BSs in Fig. 1.3(b). First, V-UE 1 uses uplink (UL) transmission which is based on single-carrier frequency-division multiple access (SC-FDMA) to send data to its connected BS. Then the BS forwards the received packet to the Serving Gateway (S-GW) via the S1-u interface. Afterwards, the S-GW performs information analysis and further forwards the data to the proper BS. Finally, the BS sends the packet to V-UE 2 through downlink (DL) transmission which is based on orthogonal frequency-division multiple access (OFDMA). Here, the Mobility Management Entity (MME) is the key control entity whose responsibilities include authentication, security, storing users' position information, and so on. Note that the examples in Fig. 1.3 assume V-UEs 1 and 2 are subscribers of the same mobile network operator. The communication procedure will become more complicated if they are served by different operators, since more logical nodes, e.g., the packet data network Gateway, will be involved in this case [12, Chapter 8].

Despite its potential applicability in vehicular environment, LTE was originally designed for mobile broadband traffic which has quite different properties and requirements with V2X traffic. Many works have been done to assess the suitability of LTE for C-ITS applications [10, 13–17]. As shown by the results, although LTE can meet the requirements of certain C-ITS services in low traffic-load scenarios, there are several deficiencies for the provision of future C-ITS applications.

- With medium or high vehicle density, the transmitted messages may easily overload

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[2] In fact, a BS is often referred to as an evolved NodeB in LTE systems. In this thesis, however, with a slight abuse of terms, we use the terms BS and eNB interchangeably for all cellular systems.

the serving BS, especially for UL communications. In addition to being a potential traffic bottleneck, the BS may become a single point of failure.

- The end-to-end delay introduced by the two-hop transmission (UL and DL) via the BS will not be satisfactory for future safety applications with more stringent latency requirement.
- This infrastructure-based approach fails when vehicles are out of coverage of the BS, e.g., in a tunnel, underground parking spot, and so on, all of which are however important scenarios to ensure traffic safety.

1.2 Future of C-ITS

Obviously, we are not living in a dichotomic world. To leverage the strengths of both ad hoc and cellular topologies, i.e., IEEE 802.11p and 3GPP LTE systems, heterogeneous vehicular network has been motivated and promoted as a promising technology to support C-ITS applications [10, 15, 18–21]. Desired characteristics of a heterogeneous vehicular network probably should embrace the following aspects.

- Exploit the local and short range communication nature of most C-ITS applications.
- Achieve high (controllable) QoS in a wide range area. This should hold no matter vehicles are in coverage of a centralized controller (e.g., a BS) or out of coverage.
- Be adaptive to rapidly varied network topologies caused by high mobility of vehicles.
- Be compatible with existing C-ITS high level layers standards.
- Be beneficial to different parties: users (including drivers, passengers, pedestrians, cyclists, and so on), telecom operators, telecom vendors, and automobile manufacturers.

Fortunately, the emerging technology of integrating direct device-to-device (D2D) communication into cellular systems indeed actualizes the idea of heterogeneous vehicular network. In D2D cellular infrastructure, two physically close UE devices can communicate with each other directly with or without the assistance of the BS. The D2D communication paradigm has been identified as one of the key technology components for future cellular systems. For instance, 3GPP has agreed that D2D communication, which was initially highlighted in Release 12, will be continuously investigated during Release 13 and Release 14 timeframes towards the LTE-advanced (LTE-A) evolution [22]. In addition, many fifth generation (5G) projects, e.g., METIS, have regarded D2D communication as one of the main technical solutions indispensable in 5G networks [23].

Recently, there is a consensus in both research and standardization activities that cellular D2D can pave the way for V2X communications [10, 11, 19, 24–28]. Detailed motivations will be discussed in Chapter 2.2. In particular, 3GPP Radio Access Networks (RAN) is currently working to enhance LTE-D2D in Release 13 in order to fulfill the requirements of V2X services (3GPP Technical Specification Group RAN Meeting #68, June 2015).

However, the investigation on D2D-based V2X is still at its infancy. Conscientious and orchestrated efforts are required for this promising direction. Many issues on PHY layer and MAC layer need to be explored before the effective provision of C-ITS applications. This lays the motivation of the thesis.

1.3 Thesis Scope and Outline

In this thesis, we investigate the use of cellular D2D links for supporting safety-related V2X communications, with focuses on MAC layer issues: radio resource management (RRM) and network synchronization. To this end, we first motivate in detail the use of D2D links for supporting V2X communications in Chapter 2. Then, depending on the specific coverage scenarios, we differentiate two modes of MAC for D2D-based V2X communications: network scheduled and autonomous, and discuss their respective research questions. As an important research question in network scheduled D2D-based V2X communication, RRM design is detailed in Chapter 3. Moreover, we study the network synchronization problem in Chapter 4, which is a crucial enabler for efficient time-division MAC mechanisms in autonomous D2D-based V2X communication. Finally, in Chapter 5, we summarize the contributions of the thesis including its appended papers, draw conclusions, and point out some possible future directions.

1.4 Notation

The following notation is used in the first part of the thesis. Sets are denoted by calligraphic letters, e.g., $\mathcal{X}$, with $|\mathcal{X}|$ denoting its cardinality. Lowercase and uppercase letters, e.g., x and X, represent scalars. Additionally, lowercase boldface letters, e.g., $\boldsymbol{x}$, designate column vectors, and uppercase boldface letters, e.g., $\boldsymbol{X}$, denote matrices. The superscript $(\cdot)^{\mathsf{T}}$ stands for the transposition, and $\mathbf{1}$ and $\mathbf{0}$ represent the all-ones column vector and the zero column vector, respectively. Unless otherwise specified, vector and matrix inequalities are interpreted element-wise.

Chapter 2

MAC of D2D-based V2X

In this chapter, we investigate at a high level the MAC layer of the D2D-based V2X communication. To this end, we first briefly introduce the concept of D2D paradigm and then motivate the promising usage of D2D links for supporting V2X communications. Moreover, we discuss the two different MAC modes that need to be applied to D2D-based V2X communication depending on the specific coverage scenario, and also present a crucial research question for each mode.

2.1 A Brief Introduction of D2D Communication

In context of cellular-based D2D communication, geographically co-located devices can communicate directly with each other without the detour via a network infrastructure, as illustrated in Fig. 2.1. This way, several types of benefits can be offered [29]. The *proximity* of devices allows for high data rate and low power consumption. The *hop gain* means using a direct D2D link instead of using both UL and DL through the network controller, e.g., the BS. Besides, traffic *offloading gain* can be attained for the cellular controller by communicating through a direct D2D link. Moreover, depending on whether or not D2D UEs (D-UEs) share the same resources used by regular cellular UEs (C-UEs), D2D networks can be divided into underlay D2D and overlay D2D. In the underlay mode, the *reuse gain* is further provided, which increases spectral efficiency.

In recent years, D2D communication has been comprehensively researched from various perspectives, including

- device discovery [30]: the first step in the establishment of a D2D link is for a device to discover the presence of other devices in order to initiate the communication with them;

- mode selection [31]: D2D communication can operate in multiple modes, e.g., direct D2D link or routing via the cellular BS, network scheduled or autonomous D2D, underlay or overlay D2D, reusing cellular UL or DL resources;

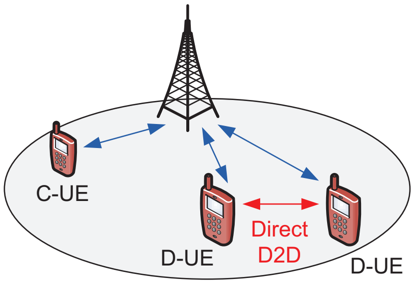


Figure 2.1: Direct D2D communication.

- RRM [32]: how C-UEs and D-UEs use or share resources and how each UE allocates its transmit power among the used resources;
- D2D clustering [33]: to further offload the traffic of the cellular BS and to maintain a workable network when the cellular infrastructure becomes damaged or dysfunctional, D-UEs can be clustered and a so-called cluster head can be elected to take over some functionalities of the cellular BS;
- design on D2D architecture [34]: how the architecture and protocol of the current cellular standards can be modified to adapt D2D communication.

In this thesis, we are not aiming at summarizing or introducing all the relevant D2D work. For more details on this line of research, readers are referred to the surveys in [29, 35–38] and the references therein. Nevertheless, we would like to mention again the classification of D2D as network scheduled D2D and autonomous D2D, which will be explicitly discussed in the rest of the thesis.

2.2 Motivation for D2D-Based V2X

Usually, safety-related C-ITS applications rely on small-message transmission in a vehicle's neighborhood, which provides them a strongly localized nature and relative small transmit buffers. Moreover, this type of applications often have to be real time and come with strict requirements on reliability and access availability.

By comparing the QoS requirements of V2X services and the potential benefits of direct D2D communication, we see that the direct D2D link is indeed a promising enabler for safety-related V2X communication. First, the localized nature of V2X application is exactly the motivating idea for D2D communication. Second, the low latency requirement of V2X services matches well the hop gain of D2D transmissions. Third, the reliability requirement of V2X communications can benefit from the proximity gain provided by the D2D link and also potentially from the centralized management at the BS. Last but not least, D2D-based V2X communication is actually appealing to operators as well, since it can bolster new business models and opportunities. Following these motivations, the

Table 2.1: Comparison of candidate technologies for V2X communication

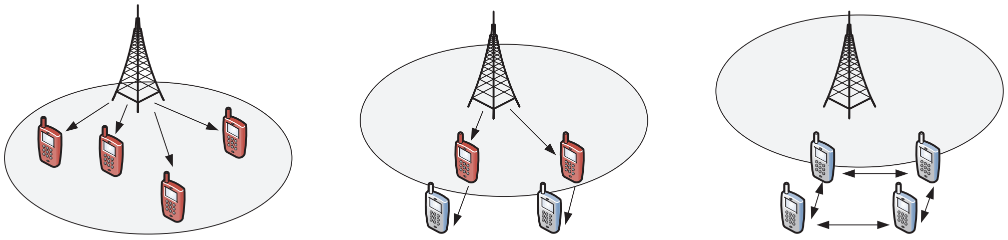
Features	**802.11p**	**LTE** (Release 8)	**Cellular-based D2D**
Access availability	Everywhere	In coverage of BS	Possibly everywhere (by differentiating network scheduled and autonomous D2D)
Controllable QoS provisioning	No (OCB as ad hoc)	Yes (management at BS)	Possibly yes (with efficient MAC)
Latency	Low	Relatively high (two-hop transmission)	Low (direct D2D link)
Local nature exploitation	Yes	No (detour via BS)	Yes (direct D2D link)
Scalability	Low (due to CSMA)	Medium (bottleneck at BS or UL)	Possibly high (with efficient MAC)
High mobility support	Yes	Yes	Yes

suitability of the D2D technique to vehicular use cases has recently been systematically evaluated in [23, 24, 26]. In parallel with the academic studies, standardization effort is being undertaken on this topic as well [27, 39–42].

In Table 2.1, we compare different candidate wireless technologies, which shows the promising usage of cellular-based D2D for our target V2X communications.

2.3 Two Modes of MAC

In cellular-based D2D systems, depending on how many devices are in coverage of the BS, D2D communication can be classified into the following three coverage scenarios shown in Fig. 2.2: *1)* in-coverage scenario where all the devices are in coverage of the BS; *2)* partial-coverage scenario where only a fraction of devices are in coverage; and *3)* out-of-coverage scenario where all the devices are out of coverage. Clearly, for different coverage scenarios, the MAC mechanisms of D2D communication have different features. Generally, a MAC mechanism decides how several transmissions share a common medium. Following the 3GPP standardization agreement (Release 13 and Release 14) [40], two modes of MAC are specified for D2D transmission: **network scheduled D2D** and **autonomous D2D**. More specifically, in network scheduled D2D, the BS schedules the exact resources used by a D-UE to transmit direct data. In autonomous D2D, on the other hand, D-UEs select transmission resources without interaction with the BS. Regarding in-coverage scenario, due to the connections from



(a) In-coverage (b) Partial-coverage (c) Out-of-coverage

Figure 2.2: Three coverage scenarios in D2D communication.

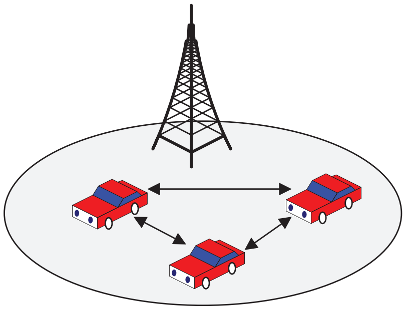


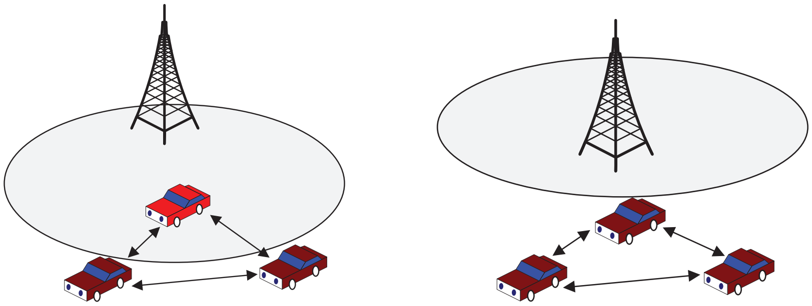
Figure 2.3: In-coverage scenario in D2D-based V2X communication.

all the devices to the BS, both network scheduled and autonomous D2D modes can be applied. In partial-coverage or out-of-coverage scenario, however, autonomous D2D mode should be the choice at least for the devices that are out of network coverage.

When using D2D links to support V2X communications, i.e., substituting the regular mobile devices in Fig. 2.2 with vehicles, there are also three different coverage scenarios depending on how many communicating vehicles are in coverage of the BS. Therefore, we likewise differentiate the two modes of MAC: network scheduled and autonomous, for D2D-based V2X communication. It is worth mentioning that this classification has already been considered in the 3GPP standardization process [1] as well as 5G research communities [43] for V2X communication.

2.3.1 Mode 1: Network Scheduled

When all the communicating vehicles are in coverage of the BS as shown in Fig. 2.3, more efficient MAC schemes can be utilized with the assistance of the BS. Specifically, the BS, as the centralized controller, can monitor the entire network and then cleverly allocate multi-dimensional resources to different transmitters. In this situation, to obtain the reuse gain of D2D and improve the spectral efficiency, we consider the UL underlay



(a) Partial-coverage (b) Out-of-coverage

Figure 2.4: Partial-coverage and out-of-coverage scenarios in D2D-based V2X communication.

D2D transmission for supporting V2X communication. Note that we choose UL channel reuse since in this case, *1)* the victim of the interference on the cellular links is at the BS which possesses advanced signal processing capabilties; *2)* the interference suffered by the V2X links can be nicely handled through spatial separation. On the other hand, if the DL reuse is applied, the transmission from the BS has serious negative impact on the V-UE receivers, which could violate the reliability requirement of safety applications. Additionally, most of the existing studies consider the UL resources to support D2D communications since there are some regulatory restrictions in certain regions for reusing the DL resources [44].

Research question: even though the BS can assist to schedule multiple transmissions, if performed poorly, using underlay D2D for V2X communication may cause significant degradation to system performance due to the interference caused by resource reuse. Moreover, guaranteeing the required latency and reliability for V2X services is demanding. Hence, the RRM strategy at the BS, including how to allocate time-frequency resources and transmit power, becomes a key design aspect to enable D2D-based V2X communication.

2.3.2 Mode 2: Autonomous

It happens that some of, or all of, the communicating vehicles are out of coverage of the BS, as illustrated by Fig. 2.4(a) and Fig. 2.4(b), respectively. This situation will disable the role that the BS can play to coordinate multiple transmissions. In this case, as a result, a possible solution is to let the V-UEs select the resources (e.g., from resource pools[1]) in an autonomous manner for their transmissions.

The autonomous mode is in fact similar to the ad hoc mode considered in IEEE 802.11p, where CSMA is the specified MAC scheme for the first generation of VANETs. Due to the principles of contention-based transmission and listen-before-transmit (as

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[1] The resource pool can be pre-configured by the BS.

described in Section 1.1.1), the poor performance of CSMA in high network load scenario has been widely recognized. Moreover, the CSMA in 802.11p is directly inherited from 802.11 technology, where the context as well as the underlying traffic and scenarios are quite different from the V2X setting. Hence, it is motivated to study other MAC layer mechanisms in addition to CSMA for the autonomous mode.

Along this direction, time-division MAC methods have been proposed to enable V2X communications, for instance, the self-organized time division multiple access (STDMA) [8], the coded slotted ALOHA [45], and so on. Compared to CSMA, their performance improvements have been shown at medium or high load scenarios. Among them, the current most mature alternative is probably STDMA, where time is divided into frames and further into time slots. Then the time slots are assigned to the transmitting UEs in a self-organized manner. In fact, STDMA has already been in commercial use in the automatic identification system (AIS), which is a mandatory position reporting system for ships larger than 300 gross ton and passenger vessels.

Research question: a common prerequisite for all time-division MAC mechanisms is an agreed notion of time. The procedure to achieve a common time reference through the entire network is called network synchronization. Clearly, the performance of the time-division MAC schemes highly depends on the accuracy of synchronization. Therefore, for autonomous D2D-based V2X communication, network synchronization is a crucial and indispensable enabler to attain the effectiveness of these time-division MAC mechanisms.

Chapter 3

RRM in Network Scheduled D2D-Based V2X Communication

As indicated previously, when the communicating vehicles are inside coverage of the BS, it is possible for the BS to coordinate transmissions, which is referred to as the network scheduled mode. In this case, to mitigate the interference resulted from resource reuse and to satisfy the distinct QoS requirements of both V-UEs and conventional C-UEs, the RRM mechanism needs to be carefully designed. In particular, the high mobility of vehicles brings more challenges regarding channel acquisition. This chapter deals with the RRM design in network scheduled D2D-based V2X communication by capturing the specific features of vehicular applications. To this end, in Section 3.1 we first discuss the major limitations when applying the conventional D2D RRM schemes to D2D-based V2X communications. In Section 3.2, we identify some important issues that require a rethinking in this regard and then summarize several RRM problem formulations in the existing literature. Finally, in Section 3.3 we present a generic RRM solution framework and its underlying theories.

3.1 Limitations of Conventional D2D RRM Strategies

RRM strategies for conventional D2D systems have been extensively researched in [29, 32, 35, 46–49], to name a few papers. Studied issues include how C-UEs and D-UEs share resources and how each UE allocates its transmit power among the resources. For more details on this line of research, readers are referred to the surveys in [29, 32, 35] and the references therein. However, we note that there are three major limitations in most of the existing D2D works for our target safety application.

Firstly, the performance objective has typically been to maximize the sum rate and prioritize cellular links [48–50]. Thus the D2D underlay is considered opportunistic as the

D2D interference to cellular links is controlled at acceptable levels. As a result, schemes for conventional D2D systems do not work well for the class of V2X applications that have small message payloads and very strict requirements on latency and reliability.

Secondly, the majority of the literature assumes that the BS is aware of the full instantaneous channel state information (CSI) of all the cellular and D2D links. This assumption, however, is too optimistic when using D2D links for V2X communications due to the highly dynamic channels associated with vehicles.

Thirdly, most works interpret the QoS requirement directly from the signal to interference plus noise ratio (SINR) viewpoint, i.e., the achieved SINR should be above a particular target value. However, it is not straightforward and clear how to obtain this target value from the original requirements of safety-critical V2X communications, which usually refer to transmission with a certain reliability and within a certain time period. For instance, the EU 5G project METIS considers that 1600 byte packets should be received within 5 ms and with a reliability of 99.999% to deliver traffic safety applications [23].

3.2 RRM Problem Formulation

3.2.1 System Model

We consider a single cell environment with M UL transmission C-UEs and K V-UEs, where the latter is counted in terms of transmitters[1]. The corresponding sets are denoted by $\mathcal{M} \triangleq \{1, 2, \ldots, M\}$ and $\mathcal{K} \triangleq \{1, 2, \ldots, K\}$, respectively. Moreover, assume the D2D underlay is only used by V-UEs that share the cellular UL resources, where the UL bandwidth is divided into F resource blocks (RBs) with $\mathcal{F} \triangleq \{1, 2, ..., F\}$ for each scheduling time unit. For C-UEs, orthogonal RB allocation applies as in LTE. On the other hand, an RB used by a C-UE can be reused by one or several V-UEs. Obviously, intra-cell interference may arise in the setup.

Fig. 3.1 illustrates the communication scenario when C-UE m, V-UE pairs k and r are sharing the same RB, where the solid and dashed lines denote the desired and the interference channels, respectively. To perform efficient RRM, the BS needs some degree of knowledge of the CSI for all involved links. On one hand, the channels connected to the BS can be measured at the BS itself; on the other hand, all other links can be measured by the corresponding receivers and then reported to the BS.

3.2.2 Important Issues Before Problem Formulation

Since safety-critical vehicular applications are quite different compared to typical D2D services, the RRM problem formulation for conventional D2D networks will not be valid here. Moreover, studies on D2D-based V2X are still in the initial stage, and thus widely acknowledged problem formulations have not been achieved yet. Therefore, in the following, we will discuss and clarify three important issues that deserve some

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[1] In general, broadcasting strategies are used for vehicular communications. Here we consider the least favorable receiving vehicle inside the intended broadcast region of each transmitting vehicle, i.e., the vehicle that has the smallest average channel power gain from the transmitting vehicle.

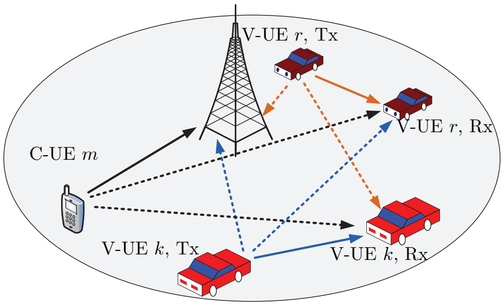

Figure 3.1: Illustration of V2X and cellular communications.

thinking and investigation before formulating a solid RRM problem for D2D-based V2X communication.

3.2.2.1 Channel Acquisition and RRM Time Scale

To indeed obtain the offloading gain of the D2D layer, the time scale of interactions between the BS and V-UEs should be much longer than the traditional LTE scheduling time interval, i.e., 1 ms. Moreover, due to mobility, the channels associated with V-UEs are typically highly time-varying. In this case, short-term RRM at the BS, such as 1 ms, requires significant overheads since the V-UEs need to report their channel measurements every millisecond or so. Even if with such short-term feedback, the obtained CSI can be outdated due to the highly dynamic channels. For these reasons, we argue that only slowly varying CSI including path loss and shadowing is likely to be available at the BS for the links associated with vehicles. In addition, the conducted RRM process should be on long-term basis for the V-UEs, e.g., a few hundred milliseconds.

3.2.2.2 Distinct Requirements of V-UEs and C-UEs

Naturally, the QoS requirements of V-UEs and C-UEs are different.

For safety-critical V2X services, there are stringent latency and reliability requirements, though high data rate is of less significance. Also, the latency requirement is usually modeled as hard deadlines, i.e., the transmitted message is considered useless when its latency exceeds the deadline and there is no additional benefit when the latency is less than the deadline. Note that this is in contrast with soft deadlines, i.e., the value of the message decreases smoothly with the latency. Moreover, the reliability requirement is often interpreted from the perspective of outage probability. Specifically, assume that E RBs are allocated to V-UE k. According to [51], the outage probability, i.e., the probability that Λ error-free bits cannot be delivered by any coding scheme, is equal to

$$p^{\text{out}} \triangleq \Pr\left\{\sum_{i=1}^{E} \rho \log_2\left(1+\gamma_i\right) < \Lambda\right\}, \tag{3.1}$$

where

$$\gamma_i \triangleq \frac{\bar{P}^{\mathrm{r}}_{k,k} H_{k,k,i}}{\sigma_k^2 + \sum_{j \neq k} \bar{P}^{\mathrm{r}}_{j,k} G_{j,k,i}} \tag{3.2}$$

is the instantaneous SINR on RB i for V-UE k. Here, $\bar{P}^{\mathrm{r}}_{k,k}$ and $\bar{P}^{\mathrm{r}}_{j,k}$ $(j \neq k)$ are average received power at the receiver of V-UE k from the desired transmitter, i.e., V-UE k, and interfering UE j, respectively, $H_{k,k,i}$ and $G_{j,k,i}$ are independent random variables that model the fast fading incurred channel power gains on RB i of the corresponding desired channel and interference channel, and σ_k^2 is the noise power at the receiver of V-UE k. The multiplication with ρ is due to the fact that an RB contains ρ complex symbols. Then, the reliability requirement can be expressed as [23]

$$p^{\mathrm{out}} \leq p_{\mathrm{o}}, \tag{3.3}$$

where p_{o} is the maximum tolerable outage probability. Note that here the outage probability is measured in terms of the aggregated number of bits that can be transmitted (i.e., the summation in (3.1)) rather than in terms of the SINR. For safety-critical V2X communications, the former is more reasonable since the requirement is usually expressed as that a certain amount of data needs to be delivered with a given probability and within a certain time period [11, 23, 52].

In contrast to safety-critical V2X applications, for typical cellular traffic, the latency requirement is much less strict and the system usually strives for high data rate subject to some level of fairness.

3.2.2.3 Requirement Transformation for V-UEs

For V-UEs, if the outage probability constraint in (3.1) is directly included in the RRM problem formulation, the RRM design will become much more complex due to the probabilistic constraint. Moreover, computational complexity will increase significantly since this probabilistic programming requires to be solved whenever resource allocation is updated. To circumvent these hurdles, we need to derive a transformation from the outage probability specification to a set of constraints that

- are computable with only slowly varying CSI because fast fading CSI is not available at the BS;
- are easy to cope with in the formulated problems;
- imply that (3.1) is satisfied.

For this purpose, a few works [53, 54] have derived mappings to relate the outage probability to an average SINR margin involving only slowly varying CSI. They interpreted outage from the perspective of SINR, i.e., the outage probability is defined as

$$\tilde{p}^{\mathrm{out}} \triangleq \Pr\left\{\gamma_i < \gamma^{\mathrm{th}}\right\}, \tag{3.4}$$

where γ^{th} is the constraint on instantaneous SINR.

However, for vehicular applications, a more reasonable measurement of outage probability is in terms of the aggregated number of transmitted bits[2] as analyzed in Section 3.2.2.2. In this case, we have in [Paper C] transformed the original probability constraint into (more strict) constraints on the number of RBs allocated to the UE and on the required average SINR of each used RB. This transformation allows us to extend certain existing D2D RRM algorithms to cater also for V2X communications with strict latency and reliability requirements.

3.2.3 Problem Formulation

In general, an RRM problem is commonly formulated as an optimization problem with an objective and several constraints. Depending on different assumptions, focuses, and targets of network design, a number of objectives and constraints have been considered for the formulations of RRM problems when supporting vehicular communications via an underlay D2D layer.

The possible objectives can include:

- Maximize the sum rate of C-UEs [55][Paper A][Paper B][Paper C];
- Minimize the interference from V-UEs to C-UEs [Paper D];
- Maximize the number of supported V-UEs [56, 57];
- Minimize the number of RBs used by V-UEs [58];
- Maximize the sum rate of V-UEs [59, 60];
- Maximize the minimum-achievable rate of V-UEs [59, 60].

It is worth mentioning that D2D-based V2X communications are not limited to only safety-critical applications. Hence, when being applied to non-safety services, data rate of vehicular networks can be of major interest. That is why the data rate of V-UEs has also been formulated as the objective to optimize in the existing works [59, 60].

Moreover, the possible constraints can include:

- Orthogonality among C-UEs;
  This is a typical assumption or constraint for C-UEs as in LTE. Since the C-UEs that are in the UL transmissions have a common receiver, i.e., the BS, the intra-cell interference can be effectively avoided by orthogonal RB allocation.
- Orthogonality among V-UEs;
  In fact, this is not a necessary constraint. For instance, in Fig. 3.1, if the involved vehicles of the two transmissions from V-UEs k and r are far away enough from each other, there is no reason why the two transmissions cannot share common

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[2] In fact, this interpretation is not limited to vehicular services. As stated in [52], in heterogeneous networks, a better definition of "outage" is the probability that no BS – or combination of BSs – can provide an aggregate data rate over some threshold.

resources. Nevertheless, imposing orthogonality on V-UEs can simplify the RRM design, since in this case the interference is only incurred between one C-UE and one V-UE. Hence, this assumption has been considered as well in [55][Paper A] and even in conventional D2D works [48, 49, 61].

- QoS requirements of C-UEs;
  The QoS requirements of C-UEs are often interpreted from the perspective of either SINR [58, 59] or limited interference from V-UEs [60]. In addition, the fairness among different C-UEs should be achieved with certain level, depending on the specific needs.
- QoS requirements of V-UEs;
  The requirements of V-UEs are usually formulated as the amount of resources assigned to a V-UE and the SINR constraint on its used resources [55–59][Paper A][Paper B][Paper C][Paper D]. However, as analyzed in Section 3.2.2.3, the original requirement of safety-critical vehicular applications is generally expressed as an outage probability constraint in terms of aggregated data rate. Therefore, how to transform the original requirement into the regular constraints that are easier to cope with is crucial for formulating a valid RRM problem.
- Max transmit power constraint per C-UE
- Max transmit power constraint per V-UE.

3.3 A Generic RRM Solution Framework

In the context of RRM, the resources usually include RBs and transmit power. Correspondingly, the RRM strategy refers to the design of how to allocate RBs and power among V-UEs and C-UEs. Since RBs and power are represented by discrete and continuous variables respectively, the formulated problems fall into the category of combinatorial optimization problem. Although not all combinatorial optimization problems are NP-hard[3], the optimal resource allocation for the setup in Section 3.2.3 usually is. Therefore, we now present a generic framework of heuristic RRM solutions including three procedures:

1. decide which RBs that can be shared by a set of UEs;
2. allocate RBs to UEs;
3. allocate transmission power to UEs.

In the following, we will explain in detail the three components and the possibly applied theories behind them. For notational convenience, in this section, we use x_i to indicate the i-th element of column vector $\boldsymbol{x}$, and $X_{i,j}$ to denote the (i,j)-th element of matrix $\boldsymbol{X}$.

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[3] We emphasize that there are indeed some combinatorial optimization or integer programming problems that can be optimally solved within polynomial time.

3.3.1 Feasibility of RB Sharing

In principle, when the orthogonality assumption on V-UEs is dispensed in the underlay D2D layer, there can be multiple UE pairs that share a common RB. However, due to interference caused by resource reuse and the SINR constraint on each UE, whether or not the sharing can indeed take place remains a question. We therefore now discuss some sufficient and necessary conditions on the feasibility of RB sharing under different power constraints.

Consider N UE pairs using the same resource for data transmission, where each UE pair has a received SINR constraint γ^{th}, i.e.,

$$\gamma_n(\boldsymbol{p}) \triangleq \frac{W_{n,n}p_n}{\sum_{j\neq n} W_{j,n}p_j + \sigma_n^2} \geq \gamma^{\mathrm{th}}, \quad n = 1, 2, ..., N. \tag{3.5}$$

Here, $\gamma_n(\boldsymbol{p})$ is defined as the received SINR of the receiver n, $W_{j,n}$ denotes the channel power gain from the transmitter j to the receiver n, p_n is the transmit power of the transmitter n, and σ_n^2 is the noise power at the receiver n. By defining

$$\Omega_{n,j} \triangleq \begin{cases} \gamma^{\mathrm{th}} W_{j,n}/W_{n,n}, & \text{if } n \neq j \\ 0, & \text{otherwise} \end{cases} \tag{3.6}$$

and $q_n \triangleq \gamma^{\mathrm{th}}\sigma_n^2/W_{n,n}$, the matrix form of (3.5) is[4]

$$(\boldsymbol{I} - \boldsymbol{\Omega})\boldsymbol{p} \geq \boldsymbol{q}, \tag{3.7}$$

where $\boldsymbol{\Omega}$ is called the inherent constraint matrix associated to the model in (3.5).

This way, the feasibility of RB sharing among the N UE pairs depends on if there exists a valid positive power vector $\boldsymbol{p}$ such that the inequality in (3.7) is satisfied. By a valid power vector, we mean a vector that includes the power values satisfying some additionally considered constraints (to be detailed later).

In the case of unlimited power, the well-known feasibility condition for the constraint in (3.7) is expressed in terms of $\rho(\boldsymbol{\Omega})$ [63], where $\rho(\boldsymbol{\Omega})$ denotes the spectral radius of matrix $\boldsymbol{\Omega}$. The feasibility problem was further investigated in [64] and [65] for the cases of max individual power constraint and sum power constraint, respectively. Moreover, the authors in [66] characterized the feasibility condition for a system with a set of additional power constraints

$$\boldsymbol{\Pi}\boldsymbol{p} \leq \bar{\boldsymbol{p}}, \tag{3.8}$$

where $\Pi_{i,j} \in \{0, 1\}$.

Recently, we have considered more general power constraints that are in the form

$$\boldsymbol{\Pi}\boldsymbol{p} \leq \bar{\boldsymbol{p}}, \tag{3.9}$$

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[4] To ease the presentation, we assume $\boldsymbol{\Omega}$ is irreducible. Replacing all non-zero entries in a matrix by one, and viewing the matrix as the adjacency matrix of a directed graph, the matrix is called irreducible if and only if such directed graph is strongly connected. The assumption of irreducibility comes with no loss of generality, because otherwise the problem decomposes into independent and smaller parts, each being associated with an irreducible inherent constraint matrix [62].

with $\mathbf{\Pi} \geq 0$, i.e., the elements of $\mathbf{\Pi}$ are non-negative. Note that (3.9) indeed generalizes the previous constraints in [64–66], i.e., max individual power constraint, sum power constraint, and the constraint in (3.8). Under (3.9), we have proposed a sufficient and necessary condition for the feasibility of RB sharing in [Paper D], which is derived based on Perron-Frobenius theory [63] and fixed point theory in power control [67].

3.3.2 RB Allocation

Usually, RB allocation results are indicated by binary variables in the formulated problems, i.e., $x_{f,k}$ equals 1 if UE k occupies RB f and 0 otherwise. In this regard, branch and bound algorithms using a divide and conquer strategy are attractive since they maintain a provable upper and lower bound on the globally optimal objective value [68]. However, when a problem is NP-hard, the worst-case complexity of branch and bound grows exponentially in the number of the binary variables. To deal with binary variables and design time-efficient RRM schemes, two mathematical tools are widely used: relaxation [69, 70] and game theory [71], where the former is done by relaxing the binary variables into real numbers and then utilizing some techniques invented for continuous optimization problems. However, both tools have their limitations. With relaxation, even if the optimum is achieved in the continuous optimization version, there can be a significant gap between it and the original problem. Besides, how to transform its solution back into a binary version remains challenging [70, 72]. Moreover, in most classical game-theoretic algorithms, equilibrium deviations and performance metrics are evaluated unilaterally per player. This way, a globally optimal solution is hardly provided [73].

Recently, matching theory has gained more and more interests in the field of wireless resource allocation [49, 73–77]. Indeed, the basic RRM problem can be posed as a matching problem between resources and users. For instance, in conventional UL multiuser transmissions where UEs are restricted to orthogonal RBs, an RB allocation problem can be formulated as a one-to-one or many-to-one bipartite matching [76]. In underlay D2D networks assuming that D-UEs cannot share RBs with each other, matching for tripartite graphs can be used to model the RB assignment problem, since the RBs, C-UEs, and D-UEs can be considered as the three disjoint sets. When the assumption on orthogonal D-UEs is further eliminated, the resource allocation problem can be formulated as hypergraph matching [74]. Due to these connections, many algorithms devised in matching theory [78] can be effectively exploited in the RRM field.

To give a flavor of the powerful matching technique, we will briefly introduce a simple type of matching – matching in bipartite graphs – and then connect it to an RRM problem.

In graph theory, a bipartite graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ is a graph whose vertex set $\mathcal{V}$ can be divided into two disjoint sets $\mathcal{A}$ and $\mathcal{B}$ such that every edge in the edge set $\mathcal{E}$ connects a vertex in $\mathcal{A}$ to one in $\mathcal{B}$. For simplicity, we further assume $|\mathcal{A}| = |\mathcal{B}|$. Additionally, a matching in a graph is a set of edges without common vertices. Then, giving an edge weight $w_{a,b}$ to each $e_{a,b} \in \mathcal{E}$, the maximum weight matching (MWM) problem is

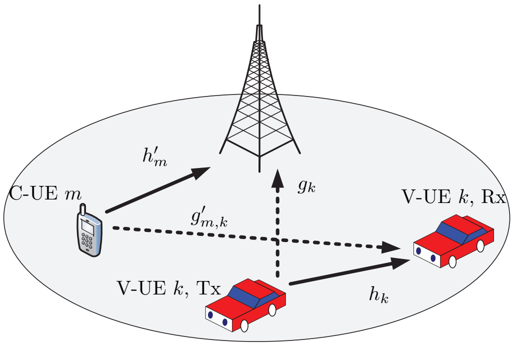

Figure 3.2: Illustration of V2X and cellular communications with orthogonal V-UEs.

formulated as [79]

$$\max_{x_{a,b}} \sum_{\substack{a\in\mathcal{A},b\in\mathcal{B}\\ \text{s.t. } e_{a,b}\in\mathcal{E}}} w_{a,b}x_{a,b} \tag{3.10}$$

subject to

$$x_{a,b} \in \{0,1\}, \quad \forall a \in \mathcal{A}, b \in \mathcal{B} \tag{3.10a}$$

$$\sum_{a\in\mathcal{A}} x_{a,b} = 1, \ \forall b \in \mathcal{B} \tag{3.10b}$$

$$\sum_{b\in\mathcal{B}} x_{a,b} = 1, \ \forall a \in \mathcal{A}, \tag{3.10c}$$

where constraint (3.10b) means that a vertex in $\mathcal{B}$ is connected to exactly one vertex in $\mathcal{A}$, and likewise, constraint (3.10c) means that a vertex in $\mathcal{A}$ is connected to exactly one vertex in $\mathcal{B}$.

Although problem (3.10) is an integer programming problem, it can be optimally solved by the Hungarian algorithm within polynomial time, where the number of operations is upper-bounded by $O(|\mathcal{A}|^3)$ [80].

Now let us shift to the RRM example. Consider a simple D2D-based V2X environment with the same number of C-UEs and V-UEs, i.e., $M = K$, where each UE needs exactly one RB. Moreover, assume that the C-UEs have been allocated RBs and the V-UEs are restricted to orthogonal RBs with each other. Fig. 3.2 illustrates the communication scenario, where C-UE m and V-UE k are using the same RB. In Fig. 3.2, h'_m and h_k are the channel power gains of the desired transmissions for C-UE m and V-UE k, respectively. Besides, $g'_{m,k}$ denotes the power gains of the interference channel from C-UE m to the receiver of V-UE k and g_k represents the interference channel power gain from V-UE k to the BS.

With these assumptions, we formulate the following RRM problem as to maximize the sum rate of C-UEs under the condition of satisfying the SINR constraint for each V-UE.

$$\max_{x_{m,k},S_m,P_k} \sum_{m=1}^{M}\sum_{k=1}^{K} x_{m,k}\log_2\left(1+\frac{S_m h'_m}{\sigma^2+P_k g_k}\right) \tag{3.11}$$

subject to

$$x_{m,k}\in\{0,1\}, \quad \forall m\in\mathcal{M}, k\in\mathcal{K} \tag{3.11a}$$

$$\sum_{k=1}^{K} x_{m,k}=1,\ \forall m\in\mathcal{M}, \quad \sum_{m=1}^{M} x_{m,k}=1,\ \forall k\in\mathcal{K} \tag{3.11b}$$

$$0\le S_m\le S^{\max},\ \forall m\in\mathcal{M}, \quad 0\le P_k\le P^{\max},\ \forall k\in\mathcal{K} \tag{3.11c}$$

$$\frac{P_k h_k}{\sigma^2+S_m g'_{m,k}}\ge x_{m,k}\gamma^{\text{th}}, \quad \forall m\in\mathcal{M}, k\in\mathcal{K}, \tag{3.11d}$$

where $x_{m,k}$ is a binary variable that equals to 1 if C-UE m and V-UE k are sharing the same RB and equals to 0 otherwise. Besides, S_m and P_k denote the transmit power of C-UE m and V-UE k, respectively. In problem (3.11), (3.11b) ensures that an RB is used by exactly one C-UE and one V-UE, (3.11c) represents the max transmit power constraint per UE, and (3.11d) guarantees the SINR constraint for each V-UE.

At a first glance, problem (3.11) seems NP-hard since it is combinatorial optimization. Nevertheless, we have proved in [Paper A] that by designing an appropriate edge weight function, which takes into account the objective function (3.11) and the constraints (3.11c) as well as (3.11d), problem (3.11) can indeed be transformed into a maximum weighted bipartite matching problem with the standard form in (3.10). This way, the optimal RRM solution to problem (3.11) is successfully achieved by the Hungarian algorithm within polynomial time.

Despite the nice outcome of problem (3.11), an RRM problem can easily become NP-hard when additional/alternative constraints/objectives are considered. Now we describe some constraints that are typical in RRM domain, which, however, incur NP-hardness.

- When the RBs need to be jointly allocated to both V-UEs and C-UEs, the vertices in the graph are divided into three disjoint sets containing RBs, V-UEs, and C-UEs respectively. In this case, the RRM problem can be interpreted as a 3-dimensional matching problem that is known to be NP-hard [81].
- When the orthogonality assumption among V-UEs is dispensed, i.e., different V-UEs are allowed to share RBs, the RRM formulation becomes NP-hard, which can be proved by reducing a partitioning problem to the RRM problem [Paper C].
- When the power constraint on either V-UE or C-UE is a sum power constraint over multiple RBs, the RRM problem becomes NP-hard due to the power coupling [Paper A].

In recent years, the Hungarian algorithm has become more and more appreciated in the RRM area [49,82–88], even though it loses its optimality for NP-hard problems. As a matter of fact, there are many other (heuristic/approximated) algorithms that have been very well developed in matching theory but currently have not been exploited enough in the RRM field. This gap affords excellent opportunities for the RRM community.

In addition to the three systematical tools stated above, i.e., relaxation, game theory, and matching theory, one can also allocate RBs directly based on some rational metrics. This kind of approaches usually leads to a good tradeoff between performance and complexity. For instance, the metrics proposed in [57][Paper B] are driven by the interpretation of spectral radius and its connection with an attainable SINR. These metrics promising results at the price of relatively low computational complexity.

3.3.3 Power Allocation

After assigning RBs to UEs, the last step of RRM is to allocate transmit power for each UE on each of its used RBs. This is typically formulated as a continuous optimization problem. In many cases, the power allocation problem possesses nice structure and thus can be transformed into convex optimization. This way, some well-know algorithms, e.g., interior point method and Newton's method [89], and even the standard optimization softwares, e.g., Yalmip [90] and CVX [91], can be used directly to solve the power allocation problem in this step. Moreover, when the problem size is large, the primary/dual decomposition method [89] can be effectively exploited to separate the problem into a set of subproblems that can then be solved in parallel. On the other hand, even if the power allocation problem cannot be transformed into convex optimization, many techniques and tricks can still be used to design approximate solutions, which have been extensively investigated in the RRM literature.

In fact, the generic solution framework and its underlying theories presented above are not limited to the RRM in D2D-based V2X communications but also applicable to a much wider range of problems, to name a few, spectrum sharing in cognitive radio [92,93], load balancing [69], and cell association [94].

Chapter 4

Network Synchronization for Autonomous D2D-Based V2X Communication

As motivated in Section 2.3.2, synchronized time is required for time-division MAC mechanisms in autonomous D2D-based V2X communication.

When each vehicle is equipped with an accurate global positioning system (GPS), synchronization throughout the entire vehicular network can be attained by synchronizing a vehicle's internal clock to the output of its GPS. More specifically, GPS receivers typically provide a precise 1 pulse per second (PPS) coordinated universal time (UTC) signal (with an error less than 100 ns), and these precise 1 PPS signals can be used for synchronization [7]. In this case, synchronization problem reduces to pairwise synchronization since there are only two nodes involved in the process and the aim is to synchronize one node to the other one. Even though pairwise synchronization is not the focus of this thesis, it is also an important topic and has been extensively researched. See [95–98] for more information on this direction.

In practice, however, accurate GPS signal may disappear in many situations, e.g., tunnels and underground parking lots. In this case, extra network synchronization protocols are needed to achieve effective time-division MAC mechanisms. From now on, we assume that no accurate GPS is available and concentrate on investigating distributed network synchronization algorithms. Here we consider distributed techniques since they are more robust to node failures and fit better for highly dynamic network topologies that are typical in vehicular environment.

In this chapter, we first give an introduction of clock models in Section 4.1. Secondly, in Section 4.2, we present the concept of timestamp-based network synchronization, which is also the approach used in the thesis. In particular, we discuss three aspects of timestamp-based synchronization, including its classification, the transmission of timestamps, and how to generate timestamps. Then we move to network synchronization problems for partial-coverage and out-of-coverage D2D-based V2X scenarios in Section 4.3 and Section 4.4, respectively, where the problem formulations, main challenges, and possible tools that can be applied are detailed for the two scenarios. Finally, in Section 4.5, we describe a further challenge on top of the two different synchronization scenarios.

4.1 Clock Model

4.1.1 Hardware Clock Model

According to the definition in [99], a hardware clock is an electronic device that counts oscillations at a particular frequency. Hence, a hardware clock usually consists of an oscillator and a counter. The oscillator is used to generate periodic events and the counter accumulates these events in order to obtain the measured time. For instance, the oscillator output can be modeled by a sinusoidal waveform,

$$\Psi(t) = A(t)\sin\Phi(t), \tag{4.1}$$

where $\Phi(t)$ is the phase,

$$A(t) = A + \Delta_A(t) \tag{4.2}$$

is the amplitude, $\Delta_A(t)$ characterizes the amplitude variation, and t denotes the global time. Note that the specific amplitude values of the oscillator are unimportant for our model. The instantaneous radian frequency function $\dot{\Phi}(t)$ can be modeled in the following form that is valid in some finite time interval $[0, t_{\max}]$ [100]

$$\dot{\Phi}(t) = \omega_0 + \sum_{u=0}^{U-1} \frac{S(u)}{u!} t^u + \dot{\xi}(t), \tag{4.3}$$

where ω_0 is a constant denoting the nominal value of the free running radian frequency of the oscillator. $S(0)$ represents the initial radian frequency error (departure). This error arises from the uncertainty which exists in the initial setting of the oscillators. The $S(u)$'s $(u = 1, ..., U-1)$[1] specify a set of time-independent values modeling the uth order radian frequency drifts, and $\dot{\xi}(t)$ is a stationary zero-mean random process characterizing the short-term oscillator instabilities.

The oscillator phase process can be obtained by integrating (4.3) from 0 to t. This results in

$$\Phi(t) = \Phi(0) + \omega_0 t + \sum_{u=1}^{U} \frac{S(u-1)}{u!} t^u + [\xi(t) - \xi(0)] \tag{4.4}$$

for $U \geq 1$. The 'value' of the hardware clock is obtained by dividing the oscillator phase by the nominal free-running radian frequency of the oscillator ω_0. Correspondingly, the

---

[1] U is a non-negative integer which indicates the order of frequency drifts we consider in the hardware clock model.

hardware clock value $T(t)$ can be expressed as

$$T(t) \triangleq \frac{\Phi(t)}{\omega_0} = T(0) + t + q(1)t + \frac{q(2)}{2}t^2 + \sum_{u=3}^{U} \frac{q(u)}{u!}t^u + \Upsilon(t), \tag{4.5}$$

where $T(0) = \Phi(0)/\omega_0$, $q(u) = S(u-1)/\omega_0$ $(u = 1, ..., U)$ are a set of values modeling the $(u-1)$th-order time drifts and $\Upsilon(t) = [\xi(t) - \xi(0)]/\omega_0$ is, in general, a nonstationary stochastic process characterizing the short-term clock instabilities.

Even though (4.5) is a complete hardware clock model in the sense that it will be accurate for smooth phase functions if U is large and t is small, it is not necessary in practice. Firstly, the values of $q(u)$ $(u = 2, ..., U)$ are small enough to be safely ignored in our target vehicular applications [101]. Moreover, in this thesis we assume $\Upsilon(t) = 0$. This is a reasonable assumption since we are not dealing with the precise measurement of time, but rather the relative time synchronization of clocks in the network [101]. This way, the important terms that characterize the performance of a hardware clock can be defined based on (4.5). These terms can also be called hardware *clock parameters*.

- *Offset*: $\theta \triangleq T(0)$.
- *Skew*: $\rho \triangleq q(1)$.
- *Frequency*: $f \triangleq 1 + q(1)$.

Then, a hardware clock model becomes

$$T(t) = ft + \theta = (1 + \rho)t + \theta, \tag{4.6}$$

which is also the hardware clock model used in the thesis.

Note that offset, skew, and frequency are all determined by the hardware clock and cannot be measured or adjusted. For a crystal oscillator commonly used in telecommunication radios, the reasonable absolute values for the maximum of skew are within the range $[1, 100]$ part per million (ppm) relative to f [102].

4.1.2 Logical Clock Model

Since the clock parameters of a hardware clock cannot be measured or adjusted manually, each vehicle also maintains a logical clock whose value is a function of the current hardware clock value. In this thesis, we assume that the function is affine and calculate the logical clock value $C(t)$ as

$$C(t) = \alpha T(t) + \beta, \tag{4.7}$$

where α $(\alpha > 0)$ and β are control parameters updated by the synchronization algorithm. This way, $C(t)$ represents the synchronized time for each vehicle. This relationship is also shown in Fig. 4.1.

Moreover, for easy presentation later, we define

$$\hat{f} \triangleq \alpha f, \quad \hat{\theta} \triangleq \alpha\theta + \beta, \tag{4.8}$$

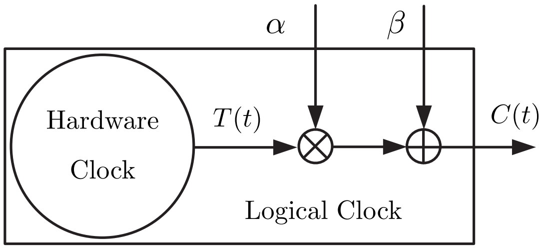

Figure 4.1: The relationship between hardware clock and logical clock.

and name them as logical clock frequency and logical clock offset. Note that $\hat{f}$ and $\hat{\theta}$ are related to the logical clock value $C(t)$. This way, we have

$$C(t) = \hat{f}t + \hat{\theta}. \tag{4.9}$$

4.2 Timestamp-Based Network Synchronization

The general goal of network synchronization is to adjust the logical clocks of different nodes throughout the entire network such that they have the same (or very close) values for any instant of t. According to what type of information is transmitted, synchronization techniques can be divided into three categories: *1)* pulse-based synchronization [103, 104], which is to synchronize the frequencies of oscillators based on emitting pulses at PHY layer; *2)* sequence-based synchronization [105, 106], which is to find the beginning of a received symbol or frame by correlating specifically designed sequences; and *3)* timestamp-based synchronization [107–114][Paper E], which is to synchronize clocks by transmitting locally recorded clock values. In fact, neither pulse-based nor sequence-based synchronization can achieve agreement on time values without additional information [115]. However, for time-division MAC schemes, a common notion of time is indispensable. Therefore, we focus on timestamp-based synchronization in this thesis.

4.2.1 Classification

Depending on what the final synchronized clock value is, timestamp-based synchronization protocols can be further grouped into the following three categories.

- Converge-to-max [107, 108], where a node only synchronizes to a transmitter that has a larger clock value than the node's own clock.

- Converge-to-leader [109–112], where one or more leader nodes with reference clocks exist and the goal is to disseminate the reference clock value throughout the entire network.

- Arbitrary-consensus [113, 114][Paper E], where an internal common time scale, which does not need to be explicitly specified, is achieved in the network through communications among neighboring nodes without relying a hierarchy.

Due to the simplicity of converge-to-max, this protocol is the technique specified in the IEEE 802.11 standard [107], which is called timing synchronization function (TSF). In 802.11 TSF, clock synchronization is achieved by periodical timing information exchange through beacon frames that contain timestamps. The lack of scalability of TSF was first analyzed in [116]. To cope with the scalability issue, the authors in [108, 116, 117] have proposed several methods to improve the TSF, where the basic principle is to make each node adjust its frequency of beacon transmission according to the received beacon messages. However, as addressed in [118], a common problem for all converge-to-max schemes is the contradiction between *fastest node asynchronism* and *time partitioning*. On one hand, since a node only synchronizes to a faster node, the clock value of the fastest node (a node with the greatest clock value in the network) will keep drifting away from other nodes, unless it becomes the beacon transmitter. This problem is called the fastest node asynchronism problem, which can be reduced by giving higher priority to the beacon transmissions of the node with a faster clock. On the other hand, the different priority will result in the time partitioning problem, where the clock values in two groups of nodes can keep on drifting away from each other, even though they are connected. Additionally, with converge-to-max schemes, malicious nodes that have ridiculously large clock values will drag the synchronized time of the entire network to an unreasonable state. Due to these reasons, we skip applying the converge-to-max principle to the design of network synchronization and focus on the other two categories.

In fact, after a closer look, we see that the synchronization requirements of partial-coverage and out-of-coverage scenarios are consistent with the principles of converge-to-leader and arbitrary-consensus, respectively. Specifically, in the partial-coverage scenario, since a fraction of vehicles are in network coverage, they can be tightly synchronized to the BS and are denoted as leaders. In addition, the other vehicles, which are denoted as followers, are not connected to the BS and thus require extra mechanisms to be synchronized. Moreover, in the out-of-coverage scenario, there is no vehicle acting as a leader since all of them are out of coverage. Correspondingly, the objective is to synchronize all the followers' clocks to a common function of the global time t. Note that it is not crucial what the function is; instead, what really matters is that the function is reasonable to represent clock model and yields the same (or very close) values for all the network nodes.

4.2.2 Transmission of Timestamps

In network synchronization, to utilize the broadcast nature of wireless media, nodes broadcast timing messages which contain the timestamps recorded by the clock of the transmitter. These messages are in turn used to adjust the clocks of the receivers. We assume that the broadcasted messages can only reach the neighbors of the transmitter, in which case the network is not necessarily fully connected.

Ideally, the transmissions from different nodes can be well coordinated by a scheduled medium access protocol, e.g., TDMA. In practice, however, a scheduled protocol is hard to implement, especially when synchronized time is not achieved and a centralized controller is absent. A more practical transmission scheme should be based on random access mechanism, where a node can broadcast at any time in any order. A widely used random broadcast scheme is contention-based transmission, where nodes contend for transmission opportunities at the beginning of each synchronization round (SR). SRs are repeated with some predetermined periodicity, and nodes are thereby granted some fairness in accessing the wireless media. As explained in [107], the transmission protocol of timing messages usually assumes that nodes are loosely synchronized at the beginning of each SR. Due to the applicability in distributed networks, the contention-based transmission mechanism is the technique specified for clock synchronization in the IEEE 802.11 standard [107] and has been used in some other works [108, 113, 119–121] as well. In this thesis, we will also use a contention-based transmission protocol.

A very basic and simple contention-based broadcast mechanism given in [107] is described as follows. Specifically, each node i

1) at the beginning of each SR, calculates a random delay τ_i that is uniformly distributed in the range $[0, Q_i]$, where Q_i is a constant defined in [107] and is the same here for all the nodes;

2) waits for the period of the random delay while decrementing the random delay timer τ_i;

3) cancels the remaining random delay and the pending transmission if a timing message arrives before the random delay timer has expired or;

4) sends a timing message when the random delay expires, i.e., $\tau_i = 0$.

With a contention-based timing message transmission protocol, a network can be represented by a directed graph $\mathcal{G}(\ell) = (\mathcal{V}, \mathcal{E}(\ell))$, where the vertex set $\mathcal{V} = \{1, 2, ..., N\}$ contains N mobile nodes (i.e., vehicles in our problem), and the edge set $\mathcal{E}(\ell)$ is defined as the set of available directed communication links during the ℓth SR.

4.2.3 MAC Layer Timestamping

Obviously, various types of delays exist within the transmissions of timing messages. Fig. 4.2 presents some possible sources of delays [109] [110], where each component is briefly analyzed as follows.

- Send time: the time spent at the sender to construct the message. Send time also accounts for the delay incurred by the packet to reach the MAC layer from the application (APP) layer. This delay is highly variable due to the software delays introduced by the underlying operating system.

- Access time: the delay incurred waiting for access to the transmit channel. This is perhaps the most critical factor contributing to the overall delay. Moreover, it is potentially highly variable in nature and is specific to the MAC protocol employed by the node.

- Transmission time: it refers to the time for a packet to be transmitted by the PHY layer, which is a function of the packet size (in bits) and the PHY-layer transmission rate (in bit/s).

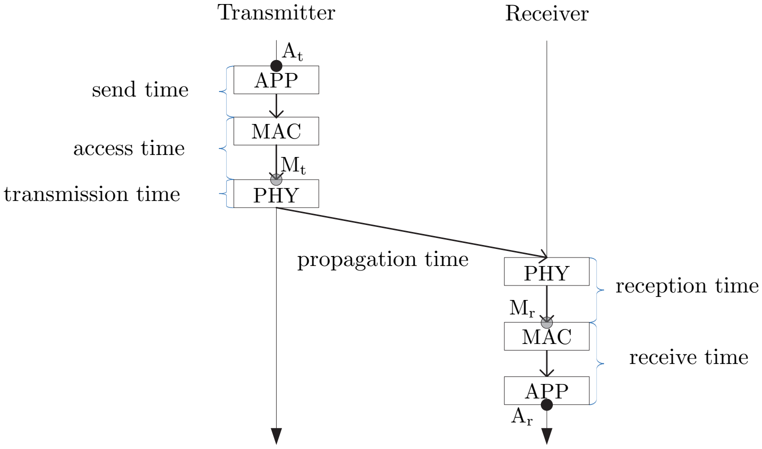

Figure 4.2: Sources of transmission delays.

- Propagation time: this is the actual time taken by the packet to traverse the wireless link from the sender to the receiver. It is depends mainly on the distance between the two nodes.

- Reception time: this refers to the time taken in receiving the bits and passing them to the MAC layer. This is going to be mainly deterministic.

- Receive time: time to process the incoming message and to notify the receiver application. Its characteristics are similar to that of send time.

Depending on which point in Fig. 4.2 we obtain timestamps, the timestamping method can be divided into APP layer timestamping and MAC layer timestamping. In APP layer timestamping, the transmitter records its timestamp when the packet enters the APP layer (i.e., at the $\mathrm{A_t}$ point), then the receiver measures its timestamp just when the packet leaves the APP layer (i.e., at the $\mathrm{A_r}$ point). On the other hand, MAC layer timestamping means that the current timestamp is written into the message payload just before the first bit of the packet is sent to the PHY layer at the transmitter (i.e., at the $\mathrm{M_t}$ point), and the timestamp at the receiver side is recorded immediately after the first bit has arrived at the MAC layer (i.e., at the $\mathrm{M_r}$ point).

In the existing works, MAC layer timestamping has been widely adopted to reduce the effects of transmission delays. In the thesis, we will also consider MAC layer timestamping. However, it is worth to point out that there will be still some delays remaining by this method, which incur inaccuracies of timestamps.

4.3 Synchronization for Partial-Coverage

In this scenario, the vehicles in coverage, called leaders, are assumed to be perfectly synchronized to the BS and have the same reference clock value $L(t)$. Then, the objective of network synchronization is to disseminate the leaders' clock values to all the followers, where the followers refer to the vehicles that are out of coverage and not directly connected to the BS. Clearly, synchronization for partial-coverage scenario falls into the category of converge-to-leader that is sometimes referred to as flooding-based synchronization.

Along this direction, the timing-sync protocol for sensor networks (TPSN) in [109] builds a spanning tree of the network in the first place, and then synchronizes nodes to their parent by estimating clock offset through a two-way message exchange. In the time diffusion synchronization protocol (TDP) proposed in [122], a leader node is temporarily elected and then a diffusion process is used to reach an equilibrium of clock values without relying network hierarchy. The flooding time synchronization protocol (FTSP) was proposed in [110], where a hierarchical structure is formed and a root node (i.e., leader) periodically floods timestamps into the network. Besides, each node adopts a linear regression table to convert between its local clock and the reference clock, and propagates its time information about the reference clock after waiting for a given period of time. Due to the waiting time duration, the propagation speed of FTSP is slow. To deal with this problem, the authors in [111] employed a clock frequency agreement algorithm among the nodes, which indeed improves synchronization accuracy and scalability of the slow-flooding scheme. Furthermore, to accelerate the spread of the reference clock, the PulseSync algorithm proposed in [112] offers rapid-flooding by allowing nodes to propagate their time information as fast as possible. Despite the promising results, the effectiveness of rapid-flooding can be significantly degraded due to neighbor contention, especially for dense networks [111].

4.3.1 Problem Formulation

The goal in the partial-coverage scenario is to synchronize all the followers to the leaders. There are mainly two challenges here.

- How to spread the leaders' clock values in a fast and reliable manner is challenging. Especially, when multiple leaders exist, how to further utilize this advantage.
- As mentioned above, some delays are still remaining even if we use MAC layer timestamping. Additionally, uncertainties exist in the process of timestamping. Hence, how to achieve highly accurate synchronization with these inaccurate timestamps is another challenge.

In a mathematical way, for each node $i \in \mathcal{V}$, the aim is to estimate the control parameters α_i and β_i based on multiple pairs of timestamps $\{L(t), T_i(t)\}$, such that

$$L(t) \approx \alpha_i T_i(t) + \beta_i, \tag{4.10}$$

where $T_i(t)$ is the hardware clock value of node i and the approximation is due to the inaccuracies of timestamps. Here, the formulated problem is closely related to regression analysis [123]. In this context, α_i and β_i are referred to as regression coefficients.

4.3.2 Strategies

Basically, tackling the two above challenges requires *fast spread* and *accurate estimation* of the leaders' clock values. For this purpose, we promote the following three strategies that can be well exploited in this regard.

Strategy 1: cooperative synchronization. Compared to the typical tree-based synchronization scheme [109] where a node only synchronizes to its fixed parent node, the timing information from other nodes should be used as much as possible to exploit the broadcast nature of wireless communication. We name this strategy as cooperative synchronization. By doing so, the leaders' clock values can be spread quickly to the followers far away from the leaders. The advantage of cooperative synchronization becomes more obvious when multiple leaders exist. Note that the idea of cooperative synchronization fits highly dynamic networks (e.g., vehicular networks) very well, since it completely removes the constraint on fixed connections between specific pairs of nodes.

Strategy 2: smart design of the timing message transmission mechanism. At a first glance, it seems tempting to endow leaders with higher probabilities to broadcast its timing information. However, due to the sharing of the common wireless media, the broadcast of leaders may block the transmission opportunities of the nodes that have been synchronized to the leaders to further flood the timing messages. To circumvent this problem, careful considerations are needed to design a transmission protocol. A possible solution, to give an example, could be assigning adaptive and different lengths of the contention windows for different nodes, i.e., adaptive and different values of Q_i in Section 4.2.2.

Strategy 3: recursive estimation. To combat inaccuracies of timestamps, a follower has to collect a sufficient number of timestamps, say Z, to estimate the regression coefficients in (4.10). In most existing works [110–112] dealing with the inaccuracy issue of synchronization, each follower keeps a regression table with dimension Z to store the most recent Z pairs of timestamps. The estimation is then recalculated using the currently stored data when a new pair arrives. In general, the larger Z is, the higher accuracy the estimation attains. However, a large Z requires a long period of timestamp collection, which will then slow down the synchronization process throughout the entire network. This brings us to the following question: is it possible to achieve both high accuracy and high spread speed? We answer it positively by utilizing the idea of recursive estimation. More specifically, assume that a follower has estimated the regression coefficients by using the first Z timestamps received from the leaders. Now, if it receives another new timestamp from a leader, it will refine its estimate such that the outcome will be the same as the estimate using all the $Z+1$ timestamps simultaneously. Details about how to apply recursive estimation to our target network synchronization can be found in [Paper F]. It is worth mentioning that, in spite of the suitability, the application of recursive estimation is surprisingly lacking in the field of network synchronization.

4.4 Synchronization for Out-of-Coverage

In this scenario, as analyzed above, the objective is to synchronize all the followers' clocks to a common function of the global time t. Moreover, it is not crucial what the function is, as long as it generates the same (or very close) values for all the followers. This indeed matches the principle of arbitrary-consensus.

4.4.1 Problem Formulation

We say that clock consensus is achieved if

$$\lim_{t \to +\infty} \frac{C_i(t)}{C_{\mathrm{v}}(t)} = 1, \quad \forall i \in \mathcal{V}, \tag{4.11}$$

where $C_i(t)$ is the logical clock value of node i and $C_{\mathrm{v}}(t) = f_{\mathrm{v}} t + \theta_{\mathrm{v}}$ ($f_{\mathrm{v}} > 0$) denotes the virtual consensus clock. Here, as is common in the literature, consensus is interpreted in the asymptotic sense. For each node i, asymptotic consensus (4.11) is equivalent to concurrently achieving the following two consensus equations:

$$\lim_{t \to +\infty} \hat{f}_i = f_{\mathrm{v}}, \quad \lim_{t \to +\infty} \hat{\theta}_i = \theta_{\mathrm{v}}, \tag{4.12}$$

i.e., the consensus on both $\hat{f}_i$ and $\hat{\theta}_i$, where $\hat{f}_i$ and $\hat{\theta}_i$ denote the logical clock frequency and offset of node i, respectively, and the values of f_{v} and θ_{v} are decided by $\mathcal{E}(\ell)$, $\{f_1, f_2, ..., f_N\}$, and $\{\theta_1, \theta_2, ..., \theta_N\}$ together.

There are mainly three challenges in this synchronization scenario.

- How to achieve global clock consensus with only local information is a challenge. In general, the underlying graph of the network is not fully connected and a node can only communicate with its neighbors. In this case, under what conditions and with what types of local operations can consensus be guaranteed for both logical clock frequencies and offsets? In particular, since the logical frequency basically represents the slope of the logical clock model (4.9), the following two requirements are sufficient for an appropriate update of the logical frequency: *1)* a local node, e.g, node i, needs to receives at least two timestamps from another node, e.g, node j; 2) the logical clocks of both node i and node j are not adjusted between the two receptions. Obviously the conditions can be satisfied if node i does not adjust its logical clock until it receives the second message from node j. However, this method will cause fairly slow convergence, especially for dense networks.

- In some special situations, running conventional consensus algorithms may lead to slow convergence and unreasonable synchronized clock values. For instance, when a new node joins an almost synchronized group, it should not cause any big change to the group. How to design efficient consensus schemes to cater for some practical synchronization situations is another challenge.

- Similar with the partial-coverage scenario, timestamps are inaccurate in practice. Then, how to guarantee the robustness of consensus-based synchronization algorithms against these inaccuracies is also challenging.

4.4.2 Tools

Consensus problems have a long history in the field of distributed computing, where the main design issues are convergence speed and resilience to inaccuracies[2]. There are tools from different areas for solving consensus problems, for instance, matrix theory, optimization theory, and control theory. Now we briefly summarize the applications of matrix theory and optimization theory in network synchronization.

4.4.2.1 Algorithms Based on Matrix Theory

As analyzed in Section 4.4.1, consensus of the logical clocks is equivalent to the consensus of both logical offsets and logical frequencies. Assume that $\boldsymbol{z}$ is a vector including the states of all nodes in the network. Here the state can be either the logical offset or the logical frequency. In this way, the update of $\boldsymbol{z}$ can be written in a vector form

$$\boldsymbol{z}^{(\ell+1)} = \boldsymbol{P}^{(\ell)}\boldsymbol{z}^{(\ell)}, \tag{4.13}$$

where ℓ is the discrete time index of the SR, $\boldsymbol{P}^{(\ell)}$ is the transfer matrix which depends on the current edge set $\mathcal{E}(\ell)$ and local operations per node. The formulation (4.13) assumes that the new state updates are linear combinations of the previous states. Therefore, the key issue in clock synchronization is to derive the matrix $\boldsymbol{P}^{(\ell)}$ by designing the local operations per node. Moreover, the authors in [124] and [125] present the sufficient conditions for $\boldsymbol{P}^{(\ell)}$ to achieve the consensus in undirected graphs and directed graphs, respectively. Note that the derivation of the conditions does not take the inaccuracy into account. Following the conditions in [124] and [125], [113, 114, 126–130] and [Paper E] propose different clock synchronization algorithms by different local operations.

4.4.2.2 Algorithms Based on Distributed Optimization

As shown in [131], the consensus problem can be formulated as an optimization problem, where the optimal solution is the average consensus. The authors in [132] apply the alternating direction multiplier method (ADMM) into the distributed clock synchronization problem, where ADMM is an iterative algorithm for solving convex minimization problems. Furthermore, in order to reduce the effects of inaccuracies, [133–136] formulate optimization problems with inaccurate timestamps, where the solution can be used to optimize the update of logical clock parameters.

4.5 A Further Challenge

As analyzed above, synchronization objectives are not exactly the same for the partial-coverage and out-of-coverage scenarios. This way, challenges for the two scenarios are also different, and thus different tools and algorithms should be applied. In addition to the respective challenges in the two synchronization scenarios, another challenge in

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[2] There are different sources of the inaccuracies, such as packet errors, transmission delays, and measurement uncertainties, where the delays and timestamping uncertainties are the key factors in network synchronization problems.

practice is that the followers initially are not aware of the coverage scenario they are in. Correspondingly, it is not clear to the followers what type of synchronization approaches to follow.

Chapter 5

Contributions, Conclusions, and Future Work

5.1 Contributions

The aim of the thesis is to motivate the use of direct D2D links in cellular systems for supporting safety-related vehicular communications and study several important MAC layer issues in this regard. For this purpose, we first give an overview of the C-ITS system including its legacy solutions and some future potentials. Then, we motivate the promising usage of D2D links for supporting V2X communications by comparing the QoS requirements of V2X services and the benefits of direct D2D communications. Moreover, we investigate at a high level the MAC layer of D2D-based V2X communication and distinguish two MAC modes, i.e., network scheduled and autonomous D2D-based V2X, depending on the specific coverage scenarios. Based on the two different MAC modes, two key research questions are further presented and studied in detail, which are RRM in the network scheduled mode and network synchronization for the autonomous mode.

5.1.1 RRM in Network Scheduled Mode

Various aspects on this topic are investigated in Chapter 3 and four appended papers [Paper A, B, C, D]. More specifically, in Chapter 3,

- to capture the particular features of safety-related vehicular applications, we identify some important issues and summarize several possible objectives as well as constraints for RRM problem formulations in network scheduled D2D-based V2X communication;

- we discuss the tractability of the optimal RRM results for solving the problems. In particular, we analyze several constraints that are typical in the RRM field but incur NP-hardness;

- we present a generic RRM solution framework consisting of three procedures and introduce some useful theoretical tools that can be well applied to each component.

Furthermore, the contributions of the four appended papers [Paper A, B, C, D] are detailed as follows.

Paper A: Radio resource management for D2D-based V2V communication Under the assumption that different V-UEs use orthogonal RBs among each other, this paper studies a centralized RRM problem for D2D-based V2V communications with strict latency and reliability requirements and with access only to slowly time-varying CSI. The main contributions are as follows.

- Assuming orthogonality among V-UEs, we proposed a method to transform the latency and reliability requirements of V2V communications into optimization constraints that are computable with only slowly varying CSI. The method allows us to extend certain existing D2D RRM algorithms to cater also for V2V communications.
- We formulate an RRM problem for allocating RBs and transmit power to a set of C-UEs and V-UEs. The problem is stated as an optimization problem with the objective to maximize the C-UE sum rate with proportional bandwidth fairness, under the constraint of satisfying the V-UEs' requirements on latency and reliability.
- We propose a two-stage heuristic algorithm, i.e., the Separate resOurce bLock and powEr allocatioN (SOLEN) algorithm, to approximately solve the RRM optimization problem. Even though the proposed SOLEN scheme is heuristic due to the division into two stages, we can achieve the optimal solution for each stage by using the theories of MWM for bipartite graphs and convex optimization.
- Various simulations are presented for performance evaluation. As shown by the results, careful RRM design is indeed necessary when applying D2D network to V2V communication. Moreover, the proposed SOLEN scheme reveals promising performance in D2D-based V2V communication.

Paper B: Resource sharing and power allocation for D2D-based safety-critical V2X communications

and

Paper C: Cluster-based RRM for D2D-supported safety-critical V2X communications

As a matter of fact, as long as link quality can be assured, allowing multiple and concurrent D2D/V2X transmissions on the same RB will not only improve spectrum efficiency, but may also lead to less interference to C-UEs due to spatial reuse. These two papers study a centralized RRM problem for D2D-supported safety-critical V2X communication, where non-orthogonal access among V-UEs is allowed. The main contributions are as follows.

- With non-orthogonal access among V-UEs, we propose an analytical method to transform the strict latency and reliability requirements of V2X communications, which are subject to random fast fading effects, into optimization constraints that are computable with slowly varying CSI only.
- Allowing non-orthogonal resource allocation for V-UEs, we formulate an RRM problem of RB sharing and power allocation for a set of C-UEs and V-UEs. This is stated as an optimization problem with the objective of maximizing the C-UE sum rate with proportional bandwidth fairness, under the constraint of satisfying the V-UEs requirements on latency and reliability.
- We analyze the NP-hardness of the formulated problem in detail. More specifically, the original RB sharing and power allocation problem is mathematically proven to be NP-hard. In addition, we also prove that even if the power levels of all UEs are given, the RB sharing problem remains NP-hard. Note this is in contrast with the orthogonal V-UE model presented in [Paper A], since the RB allocation problem in [Paper A] is optimally solved within polynomial time when the power levels of all UEs are fixed.
- Due to the NP-hardness, we propose two heuristic RRM solutions requiring only slowly varying CSI, which are referred to as the RB Sharing and Power Allocation (RBSPA) algorithm [Paper B] and the Cluster-based RB sharing and pOWer allocatioN (CROWN) algorithm [Paper C], respectively. The main difference between the two proposed algorithms lies in the metrics used to allocate RBs, where the metrics are driven by the interpretation of spectral radius in RBSPA and by matching theory in CROWN.
- Since wireless communication systems are not designed for full reliability at any cost, infeasibility is a possible outcome of the RRM problem. Hence, we discuss the use of an availability indicator [137] to notify safety-critical V2X applications of the absence of reliability.
- We provide simulations to compare the two proposed algorithms with some existing RRM methods, where improved performance is shown for both proposed schemes. Additionally, the CROWN scheme outperforms the RBSPA method at the expense of increased complexity. Furthermore, when the last power allocation stage is removed from the CROWN algorithm, the simplified version, which is called CROWN-noPA, has been shown to yield very slight performance degradation compared to CROWN.

Paper D: A novel framework for radio resource management in 5G enabled vehicular networks

This paper studies the RRM problem for enabling vehicular networks in 5G cellular systems. The main contributions are as follows.

- We motivate the use of direct D2D links to support V2V communications in 5G networks, where RRM is a key design issue. Moreover, we outline the aspects that should be considered within the RRM process when employing D2D-based V2V communications.

- We propose a novel two-stage RRM framework for integrating vehicular networks in 5G systems. In the proposed framework, the BS first allocates RB and power to V-UEs on a semi-persistent basis, and then in the second stage conducts C-UE scheduling on a dynamic basis. The benefits of the proposed framework are analyzed in detail.
- We mathematically formulate the RRM problem for the first stage. This is stated as an optimization problem with the objective to minimize the interference from V-UEs to the BS, subject to the constraints on the latency and reliability requirements of V-UEs.
- Due to the NP-hardness of the formulated problem, which is rigorously proven, we suggest a two-step heuristic algorithm to solve it. Furthermore, we briefly describe how to optimally solve the problem by a branch and bound method, which is used later in simulations as a benchmark.
- Along with the derivation of the RRM algorithm, we also propose a new sufficient and necessary condition on the feasibility of RB sharing among multiple UEs under a set of general linear power constraints.
- We evaluate the proposed RRM framework and algorithm through simulations assuming realistic system parameters and traffic models. The tentative results illustrate its promising performance. We would like to mention that the simulations are not complete yet due to time limitation. Hence, the simulation section will be updated with the final numerical results before the paper is submitted.

5.1.2 Network Synchronization for Autonomous Mode

Network synchronization is a crucial enabler for efficient time-division MAC mechanisms in autonomous D2D-based V2X communication. Various aspects on this topic are investigated in Chapter 4 and two appended papers [Paper E, F]. The investigation in Chapter 4 is conducted through three aspects: background knowledge on network synchronization, technical challenges and problem formulations for our target D2D-based V2X scenarios, and promising strategies and theoretical tools to be applied. Furthermore, the contributions of the two appended papers [Paper E, F] are detailed as follows.

Paper E: Random broadcast based distributed consensus clock synchronization for mobile networks

This paper studies the clock synchronization problem for mobile networks when there is no leader, e.g., the out-of-coverage D2D-based V2X scenario. The main contributions are as follows.

- Based on a practical random broadcast mechanism, we propose a novel Random Broadcast based Distributed consensus clock Synchronization (RBDS) scheme for dynamic networks. It is fully distributed and thus robust to node failures and changing topologies.
- The key feature of the proposed RBDS scheme is that it distinguishes between two different updates – partial updates and complete updates – for different situations. This way, the RBDS scheme can both avoid the problem of frequency over-adjustment and improve the speed of synchronization error decrease.
- In the absence of transmission delays, we theoretically prove convergence of the RBDS algorithm, which is further demonstrated by numerical results. Moreover, by utilizing a threshold for the clock update, the RBDS scheme reveals robustness even when transmission delays are present.

Paper F: Network synchronization for mobile device-to-device systems

This paper investigates the synchronization problem for mobile D2D networks, which include our target D2D-based V2X network as a special case. To the best of our knowledge, it is the first work to unify timestamp-based synchronization for both partial-coverage and out-of-coverage D2D scenarios. The main contributions are as follows.

- We formulate the network synchronization problem for mobile D2D systems, and outline the different requirements for the partial-coverage and out-of-coverage scenarios respectively. Moreover, we discuss five main challenges imposed on synchronization in mobile D2D networks.
- We analyze the theoretical principles and mathematical tools that can be exploited to handle the five challenges, and accordingly propose a low-complexity Adaptive distRibuted nEtwork Synchronization (ARES) algorithm. By using the proposed ARES scheme, fast and reliable synchronization is achieved in both scenarios.
- We provide comprehensive simulations for performance evaluation. From the results, compared to the existing methods, the ARES algorithm shows not only better synchronization accuracy and faster convergence, but also improved scalability to network size and improved robustness to timestamp inaccuracy.

5.2 Conclusions

Two major standards that are currently considered for wireless access in V2X communications are IEEE 802.11p standard and 3GPP LTE standard, and they have their respective pros and cons. To leverage the strengths of both technologies, heterogeneous vehicular network has been promoted. In this context, the emerging technology of integrating direct D2D communications into cellular systems is deemed an enabler to realize the idea of heterogenous vehicular network. Indeed, the promising usage of D2D links for supporting V2X communications is well motivated by relating the QoS requirements of V2X services and the benefits of D2D communications. However, the investigation on D2D-based V2X is still at an early stage and many issues, especially on MAC layer, need to be resolved before D2D can be used for challenging vehicular applications in an efficient manner.

In general, MAC mechanisms decide how several transmitters share a common medium. Depending on the proportion of communicating vehicles that are in network coverage, we differentiate two MAC modes, i.e., network scheduled and autonomous, for D2D-based V2X communication, where the former mode is only available for in-coverage scenario. In network scheduled D2D-based V2X, the BS can monitor the entire network and allocate resources to UEs. In this case, to cope with the intra-cell interference caused by resource reuse and to guarantee the stringent requirements of safety-related V2X services, RRM design is a key research question. Moreover, for autonomous D2D-based V2X, it has been shown that improved performance can be achieved by time-division MAC methods, which, however, require an agreed notion of time. In this case, network synchronization becomes an important research question.

Regarding RRM design in network scheduled D2D-based V2X communication, the following conclusions are drawn.

- Conventional D2D RRM strategies cannot be directly applied to V2X communications.
- Due to the peculiarities of safety-related vehicular applications, several issues require to be rethought carefully. More specifically,
  - how to include the distinct QoS requirements of both V-UEs and C-UEs in RRM problem formulation;
  - how to consider channel acquisition and the time scale of interactions within an RRM process;
  - how to transform the original latency and reliability requirements of V-UEs into the constraints that are easier to cope with.
- The RRM problems here are often formulated as combinatorial optimization problems, since the resources typically include RBs and power. Moreover, since the formulated problems are usually NP-hard in the considered setup, we provide a generic framework consisting of the following three procedures to implement heuristic RRM solutions:
  1. decide which RBs that can be shared by a set of UEs, where Perron-Frobenius theory and fixed point theory in power control can be used to design a metric that decides if an RB can be shared or not;
  2. allocate RBs to UEs, where matching theory can be a very powerful tool to utilize;
  3. allocate transmission power to UEs, where many techniques on continuous optimization problems can be exploited.

In fact, it is not necessary to include all the three procedures in a specific RRM solution. For instance, as shown in [Paper C], sometimes the last power allocation stage can be safely removed given that the optimized power levels have been taken into account within the RB allocation process.

Regarding network synchronization for autonomous D2D-based V2X communication, the following conclusions are drawn.

- When each vehicle is equipped with an accurate GPS, synchronization throughout the entire vehicular network can be attained by synchronizing a vehicle's internal clock to the output of its GPS. In this case, the synchronization problem reduces to pairwise synchronization, i.e., between a vehicle's internal clock and the output of its GPS. In many situations, however, accurate GPS signals might not be available. Then, extra network synchronization protocols are needed.
- Since the aims of network synchronization are not exactly identical for partial-coverage and out-of-coverage scenarios, different strategies and theoretical tools should be applied accordingly.
- For partial-coverage synchronization scenarios, the goal is to synchronize all the followers to the leaders, where the former and the latter refer to the vehicles outside and inside network coverage, respectively. The main challenges here are how to spread the leaders' clock values in a fast and reliable way and how to combat the inaccuracies of timestamps. Three strategies can be exploited in this regard: cooperative synchronization, smart design of the timing message transmission mechanism, and recursive estimation. In particular, since the formulated problem here is closely related to regression analysis, recursive estimation can be a powerful technique to achieve both high accuracy and high spread speed.
- For out-of-coverage synchronization scenarios, the goal is to synchronize all the followers' clocks to a common function of the global time t, which can be formulated as a consensus problem. The main challenges here are how to achieve global clock consensus with only local information, how to design more efficient consensus schemes for some practical synchronization situations (e.g., a vehicle joins an almost synchronized group), and how to be robust to the inaccuracies of timestamps. In this context, some consensus techniques including matrix theory and optimization theory can be exploited.

5.3 Future Work

Some possible future research directions are described as follows.

- How to collect reliable CSI with small signalling overhead at the BS, especially for networks with high-mobility vehicles.
- How to utilize context information, such as locations, moving directions, and the contents in the transmitted messages, to coordinate the transmissions from different UEs.

- How to support efficient V2X communications in a multi-operator environment.
- In network scheduled D2D-based V2X communication, how to design efficient handover mechanism when vehicles cross cell boundaries.
- In autonomous D2D-based V2X communication, how to design efficient channel access mechanisms that still work well in practical scenarios involving imperfect channel estimation and imperfect time synchronization.

5.4 Related Publications

Other related publications by the author, which are not included in this thesis, are listed below.

- A. Hisham, W. Sun, E. G. Ström, and F. Brännström, "Power Control for Broadcast V2V Communications with Adjacent Carrier Interference Effects," in *Proc. IEEE International Conference on Communications (ICC)*, Kuala Lumpur, Malaysia, May 2016.
- W. Sun, E. G. Ström, F. Brännström, Y. Sui, and K. C. Sou, "D2D-based V2V communications with latency and reliability constraints," in *Proc. IEEE Globecom*, Austin, TX USA, Dec. 2014.
- W. Sun, M. Gholami, E. G. Ström, and F. Brännström, "Distributed clock synchronization with application of D2D communication without infrastructure," *IEEE Globecom*, Atlanta, GA USA, Dec. 2013.
- Y. Sui, Z. Ren, W. Sun, T. Svensson, and P. Fertl "Performance study of fixed and moving relays for vehicular users with multi-cell handover under co-channel interference," *Proc. IEEE International Conference on Connected Vehicles and Expo (ICCVE)*, Las Vegas, NV USA, Dec. 2013.
- W. Sun, F. Brännström, and E. G. Ström, "On clock offset and skew estimation with exponentially distributed delays," *Proc. IEEE International Conference on Communications (ICC)*, Budapest, Hungary, June 2013.
- W. Sun, E. G. Ström, F. Brännström, and D. Sen, "Long-term clock synchronization in wireless sensor networks with arbitrary delay distributions," *Proc. IEEE Globecom 2012*, Anaheim, CA USA, Dec. 2012.
- EU FP7 INFSO-ICT-317669 METIS, D4.3, "Final report on network-level solutions," Mar. 2015.
  `www.metis2020.com/wp-content/uploads/deliverables/METIS_D4.3_v1.pdf`
- EU FP7 INFSO-ICT-317669 METIS, D2.4, "Proposed solutions for new radio access," Feb. 2015.
  `www.metis2020.com/wp-content/uploads/deliverables/METIS_D2.4_v1.pdf`

- EU FP7 INFSO-ICT-317669 METIS, D4.2, “Final report on trade-off investigations,” Aug. 2014.
  `www.metis2020.com/wp-content/uploads/deliverables/METIS_D4.2_v1.pdf`
- EU FP7 INFSO-ICT-317669 METIS, D2.3, “Components of a new air interface - building blocks and performance,” Apr. 2014.
  `www.metis2020.com/wp-content/uploads/deliverables/METIS_D2.3_v1.pdf`
- EU FP7 INFSO-ICT-317669 METIS, D2.2, “Novel radio link concepts and state of the art analysis,” Oct. 2013.
  `www.metis2020.com/wp-content/uploads/deliverables/METIS_D2.2_v1.pdf`
- EU FP7 INFSO-ICT-317669 METIS, D2.1, “Requirement analysis and design approaches for 5G air interface,” Aug. 2013.
  `www.metis2020.com/wp-content/uploads/deliverables/METIS_D2.1_v1.pdf`

Bibliography

[1] 3GPP R1-157850 TR 36 885 v0.4.0, “Study on LTE-based V2X services,” Tech. Rep., Nov. 2015.

[2] “802.11-2012-IEEE Std. for Information technology–Telecommunications and information exchange between systems Local and metropolitan area networks–Specific requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications,” IEEE, Mar. 2012.

[3] “IEEE Std. 802.11p-2010, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Amendment 7: Wireless Access in Vehicular Environment,” IEEE, Jul. 2010, superseded.

[4] H. Hartenstein and L. P. Laberteaux, “A tutorial survey on vehicular ad hoc networks,” *IEEE Commun. Mag.*, vol. 46, no. 6, pp. 164–171, June 2008.

[5] X. Wu, S. Subramanian, R. Guha, R. G. White, J. Li, K. Lu, A. Bucceri, and T. Zhang, “Vehicular communications using DSRC: Challenges, enhancements, and evolution,” *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 9, pp. 399–408, Sept. 2013.

[6] E. G. Ström, “On medium access and physical layer standards for cooperative intelligent transport systems in Europe,” *Proceedings of the IEEE*, vol. 99, no. 7, pp. 1183–1188, Jul. 2011.

[7] “1609.4-2010-IEEE Standard for Wireless Access in Vehicular Environments (WAVE)–Multi-channel Operation,” IEEE, Feb. 2011.

[8] K. Sjöberg, “Medium access control for vehicular ad hoc networks,” Ph.D. dissertation, Chalmers University of Technology, 2013.

[9] A. Festag, “Cooperative intelligent transport systems standards in Europe,” *IEEE Communications Magazine*, vol. 52, no. 12, pp. 166–172, Dec. 2014.

[10] C. Campolo, A. Molinaro, and R. Scopigno, “From today’s VANETs to tomorrow’s planning and the bets for the day after,” *Vehicular Communications*, vol. 2, no. 3, pp. 158–171, Jul. 2015.

[11] E. G. Ström, P. Popovski, and J. Sachs, "5G ultra-reliable vehicular communication," 2015. [Online]. Available: http://arxiv.org/abs/1510.01288

[12] E. Dahlman, S. Parkvall, and J. Sköld, *4G: LTE/LTE-Advanced for Mobile Broadband.* Academic Press, 1 edition, 2011.

[13] A. Vinel, "3GPP LTE versus IEEE 802.11p/WAVE: Which technology is able to support cooperative vehicular safety applications?" *IEEE Wireless Communications Letters*, vol. 1, no. 2, pp. 125–128, Feb. 2012.

[14] C. Lottermann, M. Botsov, P. Fertl, and R. Mullner, "Performance evaluation of automotive off-board applications in LTE deployments," in *Proc. IEEE Vehicular Networking Conference (VNC)*, Seoul, Korea, Nov. 2012.

[15] L. Gallo and J. Härri, "Short paper: A LTE-direct broadcast mechanism for periodic vehicular safety communications," in *Proc. IEEE Vehicular Networking Conference (VNC)*, Boston, MA, USA, Dec. 2013.

[16] Z. H. Mir and F. Filali, "LTE and IEEE 802.11p for vehicular networking: A performance evaluation," *EURASIP Journal on Wireless Communications and Networking*, vol. 2014 : 89, no. 89, pp. 1–15, May 2014.

[17] S. Kato, M. Hiltunen, K. Joshi, and R. Schlichting, "Enabling vehicular safety applications over LTE networks," in *Proc. International Conference on Connected Vehicles and Expo (ICCVE)*, Las Vegas, NV, USA, Dec. 2013.

[18] K. Trichias, "Modeling and evaluation of LTE in intelligent transportation systems," University of Twente, Tech. Rep., 2011.

[19] K. Zheng, Q. Zheng, P. Chatzimisios, W. Xiang, and Y. Zhou, "Heterogeneous vehicular networking: A survey on architecture, challenges and solutions," *IEEE Commun. Surveys & Tutorials*, vol. 17, no. 4, pp. 2377– 2396, Jun. 2015.

[20] F. Dressler, H. Hartenstein, O. Altintas, and O. Tonguz, "Inter-vehicle communication: Quo vadis," *IEEE Commun. Mag.*, vol. 52, no. 6, pp. 170–177, Jun. 2014.

[21] S. Ucar, S. C. Ergen, and O. Ozkasap, "Multi-hop cluster based IEEE 802.11p and LTE hybrid architecture for VANET safety message dissemination," *IEEE Vehicular Technology*, vol. PP, no. 99, p. 1, Apr. 2015.

[22] 3GPP RP-12209, "Study on LTE device to device proximity services," Tech. Rep., Dec. 2012.

[23] "Scenarios, requirements and KPIs for 5G mobile and wireless system," ICT-317669-METIS/D1.1, METIS deliverable D1.1, Apr. 2013. [Online]. Available: https://www.metis2020.com/documents/deliverables/

[24] A. Khelil and D. Soldani, “On the suitability of device-to-device communications for road traffic safety,” in *Proc. IEEE World Forum on Internet of Things*, Seoul, Korea, Mar. 2014.

[25] S. Mumtaz, K. M. S. Huq, and J. Rodriguez, “Cognitive vehicular communication for 5G,” *IEEE Commun. Mag.*, vol. 53, no. 7, pp. 109–117, 2015.

[26] X. Cheng, L. Yang, and X. Shen, “D2D for intelligent transportation systems: A feasibility study,” *IEEE Trans. Intelligent Transportation Systems*, vol. 16, no. 4, pp. 1784–1793, Jan. 2015.

[27] 3GPP S1-154458 TR 22 885 v1.1.0, “Study on LTE support for V2X services,” Tech. Rep., Nov. 2015.

[28] Y. Shi, X. Guo, W. Zhang, and Z. Cao, “Cellular-based technologies in next-generation V2X communications,” in *Proc. ITS World Congress*, Bordeaux, France, Oct. 2015.

[29] G. Fodor, E. Dahlman, G. Mildh, S. Parkvall, N. Reider, G. Miklos, and Z. Turanyi, “Design aspects of network assisted device-to-device communications,” *IEEE Trans. Commun. Mag.*, vol. 50, no. 3, pp. 170–177, Mar. 2012.

[30] A. Thanos, S. Shalmashi, and G. Miao, “Network-assisted discovery for device-to-device communications,” in *Proc. IEEE Globecom Workshop*, Atlanta, GA, Dec. 2013.

[31] K. Doppler, C. H. Yu, C. B. Ribeiro, and P. Janis, “Mode selection for device-to-device communication underlaying an LTE-Advanced network,” in *Proc. IEEE Wireless Communications and Networking Conference*, Sydney, Australia, Apr. 2010.

[32] P. Phunchongharn, E. Hossain, and D. I. Kim, “Resource allocation for device-to-device communications underlaying LTE-advanced networks,” *IEEE Trans. Wireless Commun.*, vol. 20, no. 4, pp. 91–100, Aug. 2013.

[33] Q. Lu, Q. Miao, G. Fodor, and N. Brahmi, “Clustering schemes for D2D communications under partial/no network coverage,” in *Proc. IEEE Vehicular Technology Conference (VTC Spring)*, Seoul, Korea, May 2014.

[34] B. Raghothaman, E. Deng, R. Pragada, G. Sternberg, T. Deng, and K. Vanganuru, “Architecture and protocols for LTE-based device to device communication,” in *Proc. IEEE International Conference on Computing, Networking and Communications*, San Diego, CA, Jan. 2013.

[35] A. Asadi, Q. Wang, and V. Mancuso, “A survey on device-to-device communication in cellular networks,” *IEEE Commun. Surveys & Tutorials*, vol. 16, no. 99, pp. 1801–1819, Apr. 2014.

[36] D. Feng, L. Lu, Y. Yuan-Wu, G. Y. Li, S. Li, and G. Feng, “Device-to-device communications in cellular networks,” *IEEE Commun. Mag.*, vol. 52, no. 4, pp. 49–55, Apr. 2014.

[37] R. Alkurd, R. M. Shubair, and I. Abualhaol, “Survey on device-to-device communications: Challenges and design issues,” in *Proc. IEEE International New Circuits and Systems Conference*, Trois-Rivieres, QC, Jun. 2014.

[38] X. Lin, J. Andrews, A. Ghosh, and R. Ratasuk, “An overview of 3GPP device-to-device proximity services,” *IEEE Commun. Magazine*, vol. 52, no. 4, pp. 40–48, May 2014.

[39] 3GPP RP-151082, “Project management of V2X in TSG RAN,” 3GPP RAN 68, Tech. Rep., 2015.

[40] 3GPP, “Chairman’s notes RAN1 76,” Tech. Rep., Feb. 2014.

[41] 3GPP RP-151109, “New SI proposal: Feasibility study on LTE-based V2X services,” Tech. Rep., Jun. 2015.

[42] 3GPP RP-151554, “Report of 3GPP TSG RAN Meeting,” Tech. Rep., Sept. 2015.

[43] “5G automotive vision,” Tech. Rep., Oct. 2015. [Online]. Available: 5g-ppp.eu/wp-content/uploads/2014/02/5G-PPP-White-Paper-on-Automotive-Vertical-Sectors.pdf

[44] G. Fodor and N. Reider, “A distributed power control scheme for cellular network assisted D2D communications,” in *Proc. IEEE GLOBECOM*, Houston, TX, USA, Dec. 2011.

[45] M. Ivanov, F. Brännström, A. Graell i Amat, and P. Popovski, “All-to-all broadcast for vehicular networks based on coded slotted ALOHA,” in *Proc. IEEE International Conference Communications Workshop*, London, UK, Jun. 2015.

[46] G. Fodor, D. D. Penda, M. Belleschi, M. Johansson, and A. Abrardo, “A comparative study of power control approaches for device-to-device communications,” in *Proc. IEEE International Conference on Communications*, Budapest, Hungary, Jun. 2013.

[47] N. Reider and G. Fodor, “A distributed power control and mode selection algorithm for D2D communications,” *EURASIP Journal on Wireless Commun. and Networking*, vol. 2012 : 266, 2012.

[48] M. Zulhasnine, C. Huang, and A. Srinivasan, “Efficient resource allocation for device-to-device communication underlaying LTE network,” in *Proc. IEEE International Conference on Wireless and Mobile Computing, Networking and Communications*, Niagara Falls, Canada, Oct. 2010.

[49] D. Feng, L. Lu, Y. Yuan-Wu, G. Y. Li, G. Feng, and S. Li, "Device-to-device communications underlaying cellular networks," *IEEE Trans. Commun.*, vol. 61, no. 8, pp. 3541–3551, Aug. 2013.

[50] R. Zhang, X. Cheng, L. Yang, and B. Jiao, "Interference-aware graph based resource sharing for device-to-device communications underlaying cellular networks," in *Proc. IEEE Wireless Communications and Networking Conference*, Shanghai, China, Apr. 2013.

[51] G. Caire, G. Taricco, and E. Biglieri, "Optimum power control over fading channels," *IEEE Trans. Inf. Theory*, vol. 45, no. 5, pp. 1468–1489, Jul. 1999.

[52] J. Andrews, "Seven ways that HetNets are a cellular paradigm shift," *IEEE Commun. Mag.*, vol. 51, no. 3, pp. 136–144, Mar. 2013.

[53] S. Kandukuri and S. Boyd, "Optimal power control in interference-limited fading wireless channels with outage-probability specifications," *IEEE Trans. Wireless Commun.*, vol. 1, no. 1, pp. 46–55, Jan. 2002.

[54] J. Papandriopoulos, S. Dey, and J. Evans, "Outage-based power control for generalized multiuser fading channels," *IEEE Trans. Commun.*, vol. 54, no. 4, pp. 693–703, Apr. 2006.

[55] W. Sun, E. G. Ström, F. Brännström, Y. Sui, and K. C. Sou, "D2D-based V2V communications with latency and reliability constraints," in *Proc. IEEE GLOBECOM Workshop*, Austin, TX USA, Dec. 2014. [Online]. Available: http://arxiv.org/abs/1501.02973

[56] M. Botsov, M. Klugel, W. Kellerer, and P. Fertl, "Location dependent resource allocation for mobile device-to-device communications," in *Proc. IEEE Wireless Communications and Networking Conference*, Istanbul, Turkey, Apr. 2014.

[57] M. Botsov., S. Stanczak, and P. Fertl, "Comparison of location-based and CSI-based resource allocation in D2D-enabled cellular networks," in *Proc. IEEE International Conference Communications*, London, UK, Jun. 2015.

[58] W. Xing, N. Wang, C. Wang, F. Liu, and Y. Ji, "Resource allocation schemes for D2D communication used in VANETs," in *Proc. IEEE Vehicular Technology Conference Fall*, Vancouver, BC, Canada, Sept. 2014.

[59] Y. Ren, C. W. W. Liu, F. Liu, and E. Liu, "Applying LTE-D2D to support V2V communication using local geographic knowledge," in *Proc. IEEE Vehicular Technology Conference Fall*, Boston, MA, USA, Sept. 2015.

[60] Y. Ren, F. Liu, Z. Liu, C. Wang, and Y. Ji, "Power control in D2D-based vehicular communication networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 12, pp. 5547–5562, Oct. 2015.

[61] T. Han, R. Yin, Y. Xu, and G. Yu, "Uplink channel reusing selection optimization for device-to-device communication underlaying cellular networks," in *Proc. IEEE International Symposium on Personal Indoor and Mobile Radio Communications*, Sydney, Australia, Sept. 2012.

[62] S. Stanczak, H. Boche, and M. Wiczanowski, "Towards a better understanding of medium access control for multiuser beamforming systems," in *Proc. IEEE Wireless Communications and Networking Conference*, New Orleans, LA, USA, Mar. 2005.

[63] S. Pillai, T. Suel, and S. Cha, "The Perron-Frobenius theorem: Some of its applications," *IEEE Trans. Signal Processing*, vol. 22, no. 2, pp. 62–75, Mar. 2005.

[64] L. A. Imhof and R. Mathar, "Capacity regions and optimal power allocation for CDMA cellular radio," *IEEE Trans. Inf. Theory*, vol. 51, no. 6, pp. 2011–2019, Jun. 2005.

[65] H. Boche and S. Stanczak, "Iterative algorithm for finding optimal resource allocations in symbol-asynchronous CDMA channels with different SIR requirements," in *Proc. the 36th Asilomar Conference on Signals, Systems, and Computers*, Pacific Grove, CA, USA, Nov. 2002.

[66] H. M. Doost, M. Ebrahimi, and A. K. Khandani, "Characterization of SINR region for interfering llink with constrained power," *IEEE Trans. Inf. Theory*, vol. 56, no. 6, pp. 2816–2828, Jun. 2010.

[67] R. Yates, "A framework for uplink power control in cellular radio systems," *IEEE J. Select. Areas Commun.*, vol. 13, no. 7, pp. 1341–1348, 1995.

[68] S. Boyd and J. Mattingley, "Branch and bound methods," 2007, notes for EE364b, Stanford University.
[Online]. Available: http://stanford.edu/class/ee364b/lectures/bb%5Fslides.pdf

[69] J. Andrews, S. Singh, Q. Ye, X. Lin, and H. Dhillon, "An overview of load balancing in HetNets: Old myths and open problems," *IEEE Wireless Commun.*, vol. 21, no. 2, pp. 18– 25, Apr. 2014.

[70] S. Gortzen and A. Schmeink, "Optimality of dual methods for discrete multiuser multicarrier resource allocation problems," *IEEE Trans. Wireless Commun.*, vol. 11, no. 10, pp. 3810–3817, Sept. 2012.

[71] Z. Han, *Game Theory in Wireless and Communication Networks: Theory, Models and Applications*, Z. Han, Ed. Cambridge University Press, 2012.

[72] M. F. Anjos and J. B. Lasserre, Eds., *Handbook on Semidefinite, Cone and Polynomial Optimization.* Springer US, 2012.

[73] Y. Gu, W. Saad, M. Bennis, M. Debbah, and Z. Han, "Matching theory for future wireless networks: Fundamentals and applications," *IEEE Commun. Mag.*, vol. 53, no. 5, pp. 52–59, May 2015.

[74] H. Zhang, L. Ma, L. Song, and Z. Han, "Wireless device-to-device hypergraph optimization," in *Proc. IEEE Conference on Computer Communications Workshop*, Toronto, ON, Canada, Apr. 2014.

[75] B. Bai, W. Chen, K. Letaief, and Z. Cao, "RBG matching: An innovative combinatorial approach for OFDMA resource allocation," in *Proc. IEEE International Conference on Communications*, Kyoto, Japan, Jun. 2011.

[76] B. Bai, W. Chen, K. B. Letaief, and Z. Cao, "Low complexity outage optimal distributed channel allocation for vehicle-to-vehicle communications," *IEEE J. Sel. Areas in Commun.*, vol. 29, no. 1, pp. 161–172, 2011.

[77] ——, "A unified matching framework for multi-flow decode-and-forward cooperative networks," *IEEE J. Sel. Areas in Commun.*, vol. 39, no. 2, pp. 397–406, Feb. 2012.

[78] M. D. Plummer and L. Lovsz, *Matching Theory.* Elsevier, 1986.

[79] M. Goemans, "Lecture notes from Michael Goemans class on combinatorial optimization." 2009. [Online].
Available: http://math.mit.edu/%7egoemans/18433S09/matching-notes.pdf

[80] "The Hungarian algorithm for weighted bipartite graphs," Tech. Rep. [Online]. Available: http://math.mit.edu/%7erpeng/18434/hungarianAlgorithm.pdf

[81] H. J. Bandelt, T. Crama, and F. C. R. Spieksma, "Approximation algorithms for multi-dimensional assignment problems with decomposable costs," *Discrete Applied Mathematics*, vol. 49, no. 1, pp. 25–50, Mar. 1994.

[82] F. Sun, V. O. K. Li, and Z. Diao, "Multiobjective optimized bipartite matching for resource allocation," in *Proc. International Symposium on Communications and Information Technologies*, Sydney, Australia, Oct. 2007.

[83] ——, "Modified bipartite matching for multiobjective optimization: Application to antenna assignments in MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 8, no. 2, pp. 1349–1355, Mar. 2009.

[84] S. Tamura, Y. Kodera, S. Taniguchi, and T. Yanase, "Feasibility of Hungarian algorithm based scheduling," in *Proc. IEEE International Conference on Systems Man and Cybernetics*, Istanbul, Turkey, Oct. 2010.

[85] S. Aslam, A. Shahid, and K. G. Lee, "IMS: Interference minimization scheme for cognitive radio networks using Hungarian algorithm," in *Proc. International Conference on Future Generation Communication Technology*, London, UK, Dec. 2012.

[86] T. Wang, F. Glineur, J. Louveaux, and L. Vandendorpe, "Weighted sum rate maximization for downlink OFDMA with subcarrier-pair based opportunistic DF relaying," *IEEE Trans. Signal Processing*, vol. 61, no. 10, pp. 2512–2524, Feb. 2013.

[87] M. R. E. Nia and S. A. Ghorashi, "A clustering scheme for resource allocation of ofdma based cellular systems," in *Proc. International Symposium on Telecommunications*, Tehran, Iran, Sept. 2014.

[88] Y. Zhang, Y. Xu, M. Gao, Q. Zhang, H. Li, I. Ahmad, and Z. Feng, "Resource management in device-to-device underlaying cellular network," in *Proc. IEEE Wireless Communications and Networking Conference*, New Orleans, LA, USA, Mar. 2015.

[89] S. Boyd and L. Vandenberghe, *Convex optimization.* Cambridge University Press, 2004.

[90] J. Lofberg, "YALMIP: A toolbox for modeling and optimization in Matlab," in *Proc. IEEE Computer Aided Control Systems Design (CACSD)*, Sept. 2004.

[91] "CVX: Matlab software for disciplined convex programming, version 2.1," CVX Research Inc., Tech. Rep., Jun. 2015. [Online]. Available: http://cvxr.com/cvx/

[92] A. Vizziello, I. F. Akyildiz, R. Agusti, L. Favalli, and P. Savazzi, "Cognitive radio resource management exploiting heterogeneous primary users," in *Proc. IEEE Globecom*, Houston, TX USA, Dec. 2011.

[93] E. Ahmed, A. Gani, S. Abolfazli, L. Yao, and S. U. Jhan, "Channel assignment algorithms in cognitive radio networks: Taxonomy, open issues, and challenges," *IEEE Commun. Surveys & Tutorials*, vol. 18, no. 1, pp. 795–823, Oct. 2014.

[94] H. Boostanimehr and V. K. Bhargava, "Unified and distributed QoS-driven cell association algorithms in heterogeneous networks," *IEEE Trans. Wireless Commun.*, vol. 14, no. 3, pp. 1650–1662, Nov. 2014.

[95] W. Sun, "On clock synchronization in wireless networks using parameter estimation and consensus techniques," Chalmers University of Technology, Gothenburg, Sweden, Tech. Rep., Dec. 2013.

[96] Y. Wu, Q. M. Chaudhari, and E. Serpedin, "Clock synchronization of wireless sensor networks," *IEEE Signal Processing Magazine*, vol. 28, no. 1, pp. 124–138, Jan. 2011.

[97] W. Sun, F. Brännström, and E. G. Ström, "On clock offset and skew estimation with exponentially distributed delays," in *Proc. IEEE International Conference on Communication*, Budapest, Hungary, Jun. 2013.

[98] W. Sun, E. G. Ström, F. Brännström, and D. Sen, "Long-term clock synchronization in wireless sensor networks with arbitrary delay distributions," in *IEEE GLOBECOM*, Anaheim, CA USA, Dec. 2012.

[99] B. Sundararaman, U. Buy, and A. D. Kshemkalyani, "Clock synchronization for wireless sensor networks: A survey," University of Illinois at Chicago, Tech. Rep., Mar. 2005.

[100] W. C. Lindsey, F. Ghazvinian, W. C. Hagmann, and K. Dessouky, “Network synchronization,” *Proceedings of IEEE*, vol. 73, no. 10, pp. 1445–1467, Oct. 1985.

[101] C. H. Rentel, “Network time synchronization and code-based scheduling for wireless ad hoc networks,” Ph.D. dissertation, Carleton University, Jan. 2006.

[102] J. E. Elson, “Time synchronization in wireless sensor networks,” Ph.D. dissertation, UCLA, 2003.

[103] G. W. Allen, G. Tewari, A. Patel, M. Welsh, and R. Nagpal, “Firefly-inspired sensor network synchronicity with realistic radio effects,” in *Proc. the 3rd ACM Conference on Embedded Networked Sensor Systems (SenSys)*, San Diego, CA, USA, Nov. 2005.

[104] S. L. Chao, H. Y. Lee, C. C. Chou, and H. Y. Wei, “Bio-inspired proximity discovery and synchronization for D2D communications,” *IEEE Commun. Letters*, vol. 17, no. 12, pp. 2300–2303, Dec. 2013.

[105] K. H. Lee, K. H. Won, and H. J. Choi, “Time synchronization method for device-to-device communication system,” in *Proc. the 7th International Conference on Ubiquitous Information Management and Communication*, New York, NY, USA, Jan. 2013.

[106] M. Morelli, C.-C. J. Kuo, and M. B. O. Pun, “Synchronization techniques for orthogonal frequency division multiple access (OFDMA): A tutorial review,” *Proceedings of the IEEE*, no. 7, pp. 1394–1427, Aug. 2007.

[107] “Wireless lan medium access control (MAC) and physical layer (PHY) specification,” IEEE Std 802.11, Nov. 1999.

[108] H. K. Pande, S. Thapliyal, and L. C. Mangal, “A new clock synchronization algorithm for multi-hop wireless ad hoc networks,” in *Proc. the 6th International Conference on Wireless Communication and Sensor Networks (WCSN)*, Allahabad, Indian, Dec. 2010.

[109] S. Ganeriwal, R. Kumar, and M. B. Srivastava, “Timing-sync protocol for sensor networks,” in *Proc. the 3rd ACM Conference on Embedded Networked Sensor Systems (SenSys)*, Los Angeles, CA USA, Nov. 2003.

[110] M. Maroti, B. Kusy, G. Simon, and A. Ledeczi, “The flooding time synchronization protocol,” in *Proc. the 4th ACM Conference on Embedded Networked Sensor Systems (SenSys)*, Baltimore, MD USA, Nov. 2004.

[111] K. S. Yildirim and A. Kantarci, “Time synchronization based on slow-flooding in wireless sensor networks,” *IEEE Trans. Parallel and Distributed Systems*, vol. 25, no. 1, pp. 244–253, Jan. 2014.

[112] C. Lenzen, P. Sommer, and R. Wattenhofer, “PulseSync: An efficient and scalable clock synchronization protocol,” *IEEE/ACM Trans. Networking*, no. 99, pp. 717–727, Mar. 2014.

[113] L. Schenato and F. Fiorentin, “Average timesynch: A consensus-based protocol for clock synchronization in wireless sensor networks,” *Automatica*, vol. 47, no. 9, pp. 1878–1886, Sept. 2011.

[114] W. Sun, M. R. Gholami, E. G. Ström, and F. Brännström, “Distributed clock synchronization with application of D2D communication without infrastructure,” in *Proc. IEEE GLOBECOM Workshop*, Atlanta, GA USA, Dec. 2013.

[115] M. Leng and Y. C. Wu, “Distributed clock synchronization for wireless sensor networks using belief propagation,” *IEEE Trans. Signal Processing*, vol. 59, no. 11, pp. 5404–5414, Nov. 2011.

[116] L. Huang and T. H. Lai, “On the scalability of IEEE 802.11 ad hoc networks,” in *Proc. the 3rd ACM International Symposium on Mobile Ad Hoc Networking and Computing*, June 2002, pp. 173–182.

[117] J. P. Sheu, C. M. Chao, and C. W. Sun, “A clock synchronization algorithm for multi-hop wireless ad hoc networks,” in *Proc. IEEE International Conf. on Distributed Computing Systems*, Tokyo, Japan, Mar. 2004.

[118] J. So and N. Vaidya, “MTSF: A timing synchronization protocol to support synchronous operations in multihop wireless networks,” University of Illinois at Urbana-Champaign, Tech. Rep., Jan. 2004.

[119] D. Zhou and T. H. Lai, “A scalable and adaptive clock synchronization protocol for IEEE 802.11-based multihop ad hoc networks,” in *Proc. IEEE Mobile Ad hoc and Sensor Conf.*, Washington, DC USA, Nov. 2005.

[120] ——, “An accurate and scalable clock synchronization protocol for IEEE 802.11-based multihop ad hoc networks,” *IEEE Trans. Parallel and Distributed Systems*, vol. 18, no. 12, pp. 1797–1808, Dec. 2007.

[121] R. Solis, V. S. Borkar, and P. R. Kumar, “A new distributed time synchronization protocol for multihop wireless networks,” in *Proc. IEEE Conference on Decision and Control*, San Diego, CA USA, Dec. 2006.

[122] W. Su and I. F. Akyildiz, “Time-diffusion synchronization protocol for wireless sensor netowrks,” *IEEE/ACM Trans. on Networking*, vol. 13, no. 2, pp. 384–397, April 2005.

[123] B. Laursen, T. D. Little, and N. A. Card, Eds., *Handbook of Developmental Research Methods*. The Guilford Press, 2013.

[124] A. Jadbabaie, L. Jie, and A. S. Morse, “Coordination of groups of mobile autonomous agents using nearest neighbor rules,” *IEEE Trans. Automatic Control*, vol. 48, no. 6, pp. 988–1001, Jun. 2003.

[125] W. Ren and R. Beard, “Consensus seeking in multiagent systems under dynamically changing interaction topologies,” *IEEE Trans. Automatic Control*, vol. 50, no. 5, pp. 655–661, May 2005.

[126] P. Sommer and R. Wattenhofer, “Gradient clock synchronization in wireless sensor networks,” in *Proc. IEEE International Conf. on Information Processing in Sensor Networks*, San Francisco, CA USA, Apr. 2009.

[127] Q. Li and D. L. Daniela, “Global clock synchronization in sensor networks,” *IEEE Trans. Computers*, vol. 55, no. 2, pp. 214–226, Feb. 2006.

[128] A. C. Pinho, D. R. Figueiredo, and F. M. G. Franga, “A robust gradient clock synchronization algorithm for wireless sensor networks,” in *Proc. IEEE International Conf. on Communication Systems and Networks*, Bangalore, India, Jan. 2012.

[129] B. J. Choi, H. Liang, X. Shen, and W. Zhuang, “DCS: Distributed asynchronous clock synchronization in delay tolerant networks,” *IEEE Trans. Parallel and Distributed Systems*, vol. 23, no. 3, pp. 1045–9219, Mar. 2012.

[130] M. K. Maggs and S. G. Okeefe, “Consensus clock synchronization for wireless sensor networks,” *IEEE Sensors Journal*, vol. 12, no. 6, pp. 2269–2277, Jun. 2012.

[131] T. Erseghe, D. Zennaro, E. DallAnese, and L. Vangelista, “Fast consensus by the alternating direction multipliers method,” *IEEE Trans. Signal Processing*, vol. 59, no. 11, pp. 5523–5537, Oct. 2011.

[132] D. Zennaro, E. DallAnese, T. Erseghe, and L. Vangelista, “Fast clock synchronization in wireless sensor networks via ADMM-based consensus,” in *Proc. IEEE International Symp. on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks*, May 2011.

[133] N. M. Freris and A. Zouzias, “Fast distributed smoothing for network clock synchronization,” in *Proc. IEEE Conf. on Decision and Control*, Maui, Hawaii, USA, Dec. 2012.

[134] I. Shames and A. N. Bishop, “Distributed relative clock synchronization for wireless sensor networks,” in *Proc. the 18th IFAC World Congress*, Milano, Italy, Aug. 2011.

[135] O. Gurewitz, I. Cidon, and M. Sidi, “Network classless time protocol based on clock offset optimization,” *IEEE/ACM Transactions on Networking*, vol. 14, no. 4, pp. 1063–6692, Aug. 2006.

[136] A. Giridhar and P. Kumar, “Distributed clock synchronization over wireless networks: Algorithms and analysis,” in *Proc. IEEE Conference on Decision and Control*, San Diego, CA, USA, Dec. 2006.

[137] “Requirement analysis and design approaches for 5G air interface,” ICT-317669-METIS/D2.1, METIS deliverable D2.1, Apr. 2013. [Online]. Available: https://www.metis2020.com/documents/deliverables/