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C 730

ACTA UNIVERSITATIS OULUENSIS

Muhammad Ikram Ashraf

RADIO RESOURCE MANAGEMENT IN DEVICE-TO-DEVICE AND VEHICLE-TO-VEHICLE COMMUNICATION IN 5G NETWORKS AND BEYOND

UNIVERSITY OF OULU GRADUATE SCHOOL;
UNIVERSITY OF OULU,
FACULTY OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING;
CENTRE FOR WIRELESS COMMUNICATIONS

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Academic dissertation to be presented with the assent of the Doctoral Training Committee of Information Technology and Electrical Engineering of the University of Oulu for public defence in the OP-Pohjola auditorium (L6), Linnanmaa, on 9 December 2019, at 12 noon

UNIVERSITY OF OULU, OULU 2019

Acta Univ. Oul. C 730, 2019

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ISBN 978-952-62-2461-9 (Paperback)
ISBN 978-952-62-2462-6 (PDF)

ISSN 0355-3213 (Printed)
ISSN 1796-2226 (Online)

Cover Design
Raimo Ahonen

JUVENES PRINT
TAMPERE 2019

Ashraf, Muhammad Ikram, Radio resource management in device-to-device and vehicle-to-vehicle communication in 5G networks and beyond.
University of Oulu Graduate School; University of Oulu, Faculty of Information Technology and Electrical Engineering; Centre for Wireless Communications
Acta Univ. Oul. C 730, 2019
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Abstract

Future cellular networks need to support the ever-increasing demand of bandwidth-intensive applications and interconnection of people, devices, and vehicles. Small cell network (SCN)-based communication together with proximity- and social-aware connectivity is conceived as a vital component of these networks to enhancing spectral efficiency, system capacity, and quality-of-experience (QoE). To cope with diverse application needs for the heterogeneous ecosystem, radio resource management (RRM) is one of the key research areas for the fifth-generation (5G) network. The key goals of this thesis are to develop novel, self-organizing, and low-complexity resource management algorithms for emerging device-to-device (D2D) and vehicle-to-vehicle (V2V) wireless systems while explicitly modeling and factoring network contextual information to satisfy the increasingly stringent requirements. Towards achieving this goal, this dissertation makes a number of key contributions.

First, the thesis focuses on interference management techniques for D2D-enabled macro network and D2D-enabled SCNs in the downlink, while leveraging users' social-ties, dynamic clustering, and user association mechanisms for network capacity maximization. A flexible social-aware user association technique is proposed to maximize network capacity. The second contribution focuses on ultra-reliable low-latency communication (URLLC) in vehicular networks in which interference management and resource allocation techniques are investigated, taking into account traffic and network dynamics. A joint power control and resource allocation mechanism is proposed to minimize the total transmission power while satisfying URLLC constraints.

To overcome these challenges, novel algorithms are developed by combining several methodologies from graph theory, matching theory and Lyapunov optimization. Extensive simulations validate the performance of the proposed approaches, outperforming state-of-the-art solutions. Notably, the results yield significant performance gains in terms of capacity, delay reductions, and improved reliability as compared with conventional approaches.

Keywords: 5G, clustering, D2D, Lyapunov optimization, matching theory, radio resource management, URLLC, V2V

Ashraf, Muhammad Ikram, Radioresurssien hallinta laitteesta laitteeseen ja ajoneuvosta ajoneuvoon välisessä viestinnässä 5G- ja tulevaisuuden verkoissa.
Oulun yliopiston tutkijakoulu; Oulun yliopisto, Tieto- ja sähkötekniikan tiedekunta; Centre for Wireless Communications
Acta Univ. Oul. C 730, 2019
Oulun yliopisto, PL 8000, 90014 Oulun yliopisto

Tiivistelmä

Tulevaisuuden solukkoverkkojen pitää pystyä tukemaan yhä suurempaa kaistanleveyttä vaativia sovelluksia sekä yhteyksiä ihmisten, laitteiden ja ajoneuvojen välillä. Piensoluverkkoihin (SCN) pohjautuvaa tietoliikennettä yhdistettynä paikka- ja sosiaalisen tietoisuuden huomioiviin verkkoratkaisuihin pidetään yhtenä elintärkeänä osana tulevaisuuden solukkoverkkoja, joilla pyritään tehostamaan spektrinkäytön tehokkuutta, järjestelmän kapasiteettia sekä kokemuksen laatua (QoE). Radioresurssien hallinta (RRM) on eräs keskeisistä viidennen sukupolven (5G) verkkoihin liittyvistä tutkimusalueista, joilla pyritään hallitsemaan heterogeenisen ekosysteemin vaihtelevia sovellustarpeita. Tämän väitöstyön keskeisinä tavoitteina on kehittää uudenlaisia itseorganisoituvia ja vähäisen kompleksisuuden resurssienhallinta-algoritmeja laitteesta-laitteeseen (D2D) ja ajoneuvosta-ajoneuvoon (V2V) toimiville uusille langattomille järjestelmille, sekä samalla mallintaa ja tuottaa verkon kontekstikohtaista tietoa vastaamaan koko ajan tiukentuviin vaatimuksiin. Tämä väitöskirja edistää näiden tavoitteiden saavuttamista usealla keskeisellä tuloksella.

Aluksi väitöstyössä keskitytään häiriönhallinnan tekniikoihin D2D:tä tukevissa makroverkoissa ja laskevan siirtotien piensoluverkoissa. Käyttäjän sosiaalisia yhteyksiä, dynaamisia ryhmiä sekä osallistamismekanismeja hyödynnetään verkon kapasiteetin maksimointiin. Verkon kapasiteettia voidaan kasvattaa käyttämällä joustavaa sosiaaliseen tietoisuuteen perustuvaa osallistamista. Toinen merkittävä tulos keskittyy huippuluotettavaan lyhyen viiveen kommunikaatioon (URLLC) ajoneuvojen verkoissa,
joissa tehtävää resurssien allokointia ja häiriönhallintaa tutkitaan liikenteen ja verkon dynamiikka huomioiden. Yhteistä tehonsäädön ja resurssien allokoinnin mekanismia ehdotetaan kokonaislähetystehon minimoimiseksi samalla, kun URLLC rajoitteita noudatetaan.

Jotta esitettyihin haasteisiin voidaan vastata, väitöstyössä on kehitetty uudenlaisia algoritmeja yhdistämällä graafi- ja sovitusteorioiden sekä Lyapunovin optimoinnin menetelmiä. Laajat tietokonesimuloinnit vahvistavat ehdotettujen lähestymistapojen suorituskyvyn, joka on parempi kuin uusimmilla nykyisillä ratkaisuilla. Tulokset tuovat merkittäviä suorituskyvyn parannuksia erityisesti kapasiteetin lisäämisen, viiveiden vähentämisen ja parantuneen luotettavuuden suhteen verrattuna perinteisiin lähestymistapoihin.

Asiasanat: 5G, D2D, Lyapunov-optimointi, radioresurssien hallinta, ryhmittely, sovitusteoria, URLLC, V2V

Dedicated to the nearest person to my heart, the (late) Sufi Alhaj Habib-Ullah Havi, my beloved parents and family

Acknowledgements

In the name of Allah, the most Beneficent, the most Merciful. It has been an inspiring and rewarding journey towards the completion of my doctoral thesis at the Centre for Wireless Communication (CWC), in the Faculty of Information Technology and Electrical Engineering at the University of Oulu, Finland. This work would not have been possible without the encouragement, support, and guidance from many individuals and collaborators.

First, I am deeply obliged to thank my supervisor Associate Professor Mehdi Bennis for providing the opportunity to pursue my doctoral studies. Thank you for all the inspiring guidance, fruitful discussions, constructive comments, and endless patience. More importantly, thank you for your unconditional support and encouragement whenever I could not see the light at the end of the tunnel. Not only did you give me the motivation to address important research challenges, but also constantly present with tremendous technical supervision and great humanity.

My greatest gratitude goes to Professor Walid Saad from Wireless@Virginia Tech, for his immense support, comments and constructive criticism since from the beginning of my doctoral studies. Furthermore, I would like to give my sincere appreciation to my co-supervisor Professor Marcos Katz for his support. I am also thankful to Professor Matti Latva-aho and Professor Markku Juntti for providing me the opportunity to carry out my research at CWC after Nokia recession. This thesis was financially supported by several projects namely, GREEN-T, WiFiUS and COIN. I would also like to thank my follow-up group, Adjunct Professor Matti Hämäläinen, Professor Jari Iinatti and Dr. Pekka Pirinen for their insightful advices and meticulous suggestions, which made my doctoral research productive and stimulating.

I would like to thank the pre-examiners of my thesis, Professor Muhammad Ali Imran (University of Glasgow, UK) and Professor Tapani Ristaniemi (University of Jyväskylä, Finland), for their valuable comments that improved the quality of my work. I am also deeply grateful to Associate Professor Mario Di Francesco (Aalto University, Finland) for acting as an opponent for my doctoral defense.

I would also like to extend my thanks to Zach Shelby who supervised my Master thesis and gave me the opportunity to start my research career in Oulu. Furthermore, I would like to extend my gratitude to Dr. Shahid Mumtaz and Dr. Aamir Mahmood for their valuable collaboration and encouragements. I thank Johan Torsner from Ericsson for encouraging me to complete my doctoral thesis. I would also like to thank Dr. Kimmo Hiltunen for reviewing my thesis.

I cherished the opportunity of working with several talented co-workers and collaborators. I am grateful to Dr. Sumudu Samarakoon with whom I had the privilege of having several fruitful discussions. I am also very appreciative of my co-workers especially Chen-Feng Liu, Syed Tamoor-ul-Hassan, Mohammed S. ElBamby, Dr. Ganesh Venkatraman, Dr. Satya Joshi, Dr. Petri Luoto, Cristina Perfecto, Dr. Leonardo Goratti, Dr. Helal Chowdhury, Dr. Hamidreza Bagheri, Dr. Juha Petäjäjärvi, Dr. Zaheer Khan and Dr. Ali Cagatay Cirik for their productive discussions and fruitful meetings. I would like to thank all the administrative staff: Kirsi Ojutkangas, Jari Sillanpaa, Maritta Juvani, Varpu Pitkänen, Anu Niskanen, Eija Pajunen, Elina Komminaho and Hanna Saarela for their cooperation in every step of this journey.

I am very fortunate to have wonderful friends in Oulu: Abdul Basit, Shahid Rehan, Saadullah, Zeeshan, Babar, Zubair, Irtaza, Abdul Moiz, Kamran Khalid, Kamran Aslam, Mudassir, Rana Sajaad, Haresh, Nouman, Hassan, Giorgio, Francesco, Animesh, Sharat, Abdenour Hadid, Khaled Abass, Suliman, Khalid Bur, Dr. Khaled and many others for providing an enormous social support during my stay in Oulu. I also thank my best friends abroad Zahid, Farhan, Haroon, Nouman and Junaid for their support. My friend Ali Arshed deserves my most sincere appreciation for his encouragement, especially during times of hardships.

Last but foremost, I owe much of this thesis to my loving parents, siblings and their families for love and support they have provided throughout my life. Above all, I would like to express my heartfelt gratitude to my mentor the (late) Sufi Alhaj Habib-Ullah Havi, my (late) grandparents, my loving parents Muhammad Ashraf, Kalsoom Akhtar, my wife Mehwish Ikram and my lovely son Muhammad Sarim Ikram for their love and care, for being the ultimate courage and strength of my life. Thank you very much for all encouragement and support to achieve this milestone, which would have not been possible without all of you. This thesis is dedicated to them.

Espoo, Finland, October 2019 Muhammad Ikram Ashraf

List of abbreviations

Acronyms:

5G	Fifth generation
3GPP	3rd Generation partnership project
AWGN	Additive white Gaussian noise
BS	Base station
CAM	Cooperative awareness message
CCDF	Complementary cumulative density function
CDF	Cumulative density function
C-ITS	Cooperative intelligent systems
CSI	Channel state information
D2D	Device-to-device
DENM	Decentralized environmental notification message
EE	Energy efficiency
ETSI	European telecommunications standards institute
FDD	Frequency division duplex
GPS	Global positioning system
HetNet	Heterogeneous network
IEEE	Institute of electrical and electronics engineers
IoT	Internet-of-things
ITS	Intelligent transportation system
LOS	Line-of-sight
LTE	Long-term evolution
NLOS	Non-line-of-sight
MAC	Medium access control
MC	Mobile cloud
METIS	Mobile and wireless communications enablers for the twenty-twenty information society
MNO	Mobile network operator
PCH	Primary cluster head
ProSe	Proximity service discovery
QoS	Quality-of-service

QoE	Quality-of-experience
QSI	Queue state information
RRM	Radio resource management
RB	Resource block
RSRP	Reference signal received power
RSU	Roadside unit
SCBS	Small cell base station
SCH	Secondary cluster head
SCN	Small cell network
SINR	Signal to interference and noise ratio
SN	Serving node
UE	User equipment
URLLC	Ultra-reliable low-latency communication
V2P	Vehicle-to-pedestrian
V2V	Vehicle-to-vehicle
V2I	Vehicle-to-Infrastructure
VUE	Vehicle user equipment
V2X	Vehicle-to-everything

Roman-letter notations:

$\boldsymbol{A}$	Similarity matrix between UEs
$\boldsymbol{C}$	Weighted cost matrix
$\boldsymbol{D}$	Distance based similarity matrix
$\boldsymbol{E}$	Edge betweenness centrality matrix among UEs
$\boldsymbol{L}$	Load based dissimilarity matrix
$\boldsymbol{P}$	Power matrix
$\boldsymbol{X}$	RB allocation matrix
$\boldsymbol{Y}$	Gaussian affinity matrix
$\boldsymbol{W}$	Social distance matrix
BW	System bandwidth
$\mathcal{B}$	Set of SCBSs
$\mathcal{I}$	Set of important UEs
$\mathcal{K}$	Set of VUEs
$\mathcal{L}_b$	Set of nodes served by node b

$\mathcal{M}$	Set of UEs
$\mathcal{N}$	Set of RBs
$\mathcal{S}$	Set of SNs
$\mathcal{Z}$	Set of cluster
B	Total number of SCBSs
I	Total number of important UEs
K	Total number of VUEs
M	Total number of UEs
N	Total number of RBs
S	Total number of SNs
Z	Total number of clusters
$d_{m\tilde{m}}$	Euclidean physical distance between node m and $\tilde{m}$
$\boldsymbol{f}, \boldsymbol{j}$	Virtual queue vectors
h_{bm}	Channel gain between node b and node m
I_{kn}	Aggregated interference at VUE k on the RB n
N_0	Noise spectral density
p_{kn}	Power at VUE k over RB n
$P_k^{\max}$	Total power budget at VUE k
R_{em}	Rate between transmitter e and receiver m
$R_{bm}^{\max}$	Maximum rate between SCBS b and UE m neglecting the interference from other SCBSs
t	time slot
T	Time duration for a frame
x_{kn}	Indicator variable shows VUE k uses RB n
U_{sm}	Utility of UE m with respect to SN s
U_s	Utility of SN s
v	Non-negative trade-off parameter
$\boldsymbol{v}_b$	Geographical coordinates of node b

Greek-letter notations:

τ	time slot duration
η	Matching game
$\boldsymbol{\eta}$	Network wide matching vector
ϕ_b	cell load of SCBS b

ρ_{kn}	Time load over RB n by VUE k
σ_d	Parameter that controls the impact of neighborhood size in similarity
σ_l	Parameter that controls the range of load in dissimilarity
Ψ_m	Residual energy of UE m
σ_l	Parameter that controls the range of load in dissimilarity
α^{SIM}	Parameter that controls the impact of similarities between nodes
α^{EBW}	Parameter that controls the impact of edge betweenness between nodes
ω	Bandwidth of an RB
Υ_d	Gaussian distance similarity range for any two connected nodes
ρ_{kn}	Time load over RB n by VUE k
ϕ_k	Traffic influx rate at VUE k
λ_k	Packet arrival rate at VUE k
Ω	Weight of distance-based similarity on joint similarity

Mathematical operator notations and symbols:

$\|\mathcal{X}\|$	Cardinality of the set $\mathcal{X}$
$\|\|\boldsymbol{x}\|\|$	Euclidean norm of vector $\boldsymbol{x}$
$\mathbb{E}[\cdot]$	Expectation function
$\mathbb{1}(x)$	Indicator function
x^+	Returns x if $x > 0$ and 0 otherwise

List of original publications

This thesis is based on the following articles, which are referred to in the text by their Roman numerals (I–VI):

I Ashraf MI, Bennis M, Saad W & and Katz M (2014) Exploring social networks for optimized user association in wireless small cell networks with device-to-device communications. In: IEEE Wireless Communications and Networking Conference Workshops (WCNCW), Istanbul, 224–229.

II Ashraf MI, Bennis M, Perfecto C & Saad W (2016) Dynamic Proximity-Aware Resource Allocation in Vehicle-to-Vehicle (V2V) Communications. In: IEEE Globecom Workshops (GC Wkshps), Washington, DC, 1–6.

III Ashraf MI, Hassan ST, Mumtaz S, Tsang KF & Rodriquez J (2016) Device-to-device assisted mobile cloud framework for 5G networks. In: IEEE 14th International Conference on Industrial Informatics (INDIN), Poitiers, 1020–1023.

IV Ashraf MI, Bennis M, Saad W, Katz M & Hong CS (2017) Dynamic Clustering and User Association in Wireless Small-Cell Networks With Social Considerations. IEEE Transactions on Vehicular Technology, 66(7): 6553–6568.

V Ashraf MI, Liu CF, Bennis M & Saad W (2017) Towards Low-Latency and Ultra-Reliable Vehicle-to-Vehicle Communication. In: European Conference on Networks and Communications (EuCNC), Oulu, 1–5.

VI Ashraf MI, Liu CF, Bennis M, Saad W, Katz M & Hong CS (2018) Dynamic Resource Allocation for Optimized Latency and Reliability in Vehicular Networks. IEEE Access (6), 63843–63858.

Contents

1 Introduction

1.1 Motivation

Operators face an unprecedented demand for mobile data traffic. Mobile data traffic (e.g., data, voice, online video streaming, etc.) will be expected to grow three-fold between 2019 to 2022 [1]. Total mobile data traffic is forecast to rise at a compound annual growth rate (CAGR) of 43 percent, reaching close to 107 exabytes (EB) per month by the end of 2023 [2]. The dramatic increase in data traffic is mainly due to the proliferation of smart devices and bandwidth intensive wireless applications. In addition to personal applications, new futuristic services (e.g., Internet of things (IoT), vehicular communication, wearable devices for home security and healthcare) are also contributing to the global mobile traffic growth. In addition to human-centric traffic, the number of cellular IoT connections is growing at an annual rate of 30% and expected to reach 3.5 billion in 2023 [2]. As expected, these trends pose significant challenges to mobile network operators (MNOs) with existing cellular network technologies to meet the spectrum demand and accommodate the stringent requirements for data-hungry applications.

The proliferation of bandwidth-intensive wireless applications such as multimedia streaming and online social networking (OSN) has led to a tremendous increase in wireless spectral resources [3]. In addition to the above-mentioned expectations, wireless devices in fifth generation (5G) networks are expected to be constantly interacting with each other as well as with their environment (e.g., data communications from wireless sensors to devices). This increasing need for wireless capacity mandates novel cellular architectures for delivering high quality-of-service (QoS) cost-effectively. In this respect, small cell networks (SCNs), built on the premise of deploying inexpensive, low-power small cell base stations (SCBSs) are instrumental in boosting wireless capacity and offloading traffic. Reaping the benefits of SCNs requires overcoming several challenges that include user association, traffic offloading, and radio resource management (RRM), among others [3, 4, 5, 6]. Along with the rapid proliferation of SCNs, cellular systems are moving from a base station (BS) to a user-centric architecture driven by the surge of user-centric applications [7]. It is anticipated that a large number of devices with varying QoS requirements will interact within small coverage footprints [7]. In parallel to that, in conjunction with SCNs, device-to-device (D2D) based cellular communication is a promising technique to further improve the performance of SCNs, in which D2D devices communicate directly bypassing the infrastructure yielding increased network capacity, extended coverage, enhanced data offload and improved energy efficiency [7, 8, 9, 10, 11, 12].

In addition to semi-static D2D communication, vehicle-to-vehicle (V2V) communication is one of the most promising enablers for intelligent transportation systems (ITSs) [13]. Considering the limitations of the current solutions for vehicular applications, integrating D2D links into cellular systems is a promising technology for vehicular communications. However, the investigation of D2D-based V2V communication is still in its infancy and many issues, especially interference management due to resource reuse need to be studied. In fact, to boost capacity and increase reliability, D2D communication links are a key enabler for V2V communication due to the localized nature of V2V services and QoS in terms of latency (i.e., hop gain of D2D) and reliability (i.e., proximity gain provided in D2D). *Ultra-reliable and low-latency communication (URLLC)* is crucial for ensuring vehicular traffic safety and mission-critical applications.

Although futuristic vehicles (e.g., modern vehicles, electric vehicles) are usually equipped with multiple sensors, e.g., lane change alerts and automatic braking, safety concerns in autonomous transportation and other mission-critical applications still pose significant challenges for vehicular networks. V2V safety services aim at reducing the risk of traffic accidents. In this regard, the European telecommunications standards institute (ETSI) has standardized two safety messages: cooperative awareness message (CAM) and decentralized environmental notification message (DENM) [14, 15]. Transmitting these messages with ultra-reliability and low latency is crucial [16]. Legacy solutions for V2V communications rely on ad-hoc communication over the IEEE 802.11p standard and backend-based communications over the LTE cellular standard, which suffer from unbounded latency and varying QoS guarantees [17, 18]. To support cooperative automated applications with closed-loop control, such as vehicle collision avoidance, safety-critical applications, end-to-end or round-trip latency requirement is around 1 ms while the overall packet loss probability is below 99.999 % for small packet sizes, e.g., 20 bytes or even smaller [19, 20, 21]. Queuing latency is one of the main factors contributing to minimizing the end-to-end delay. According to Nokia's 5G URLLC vision, a target queuing latency of 0.125 ms is required to satisfy 1 ms end-to-end latency bound [22]. Furthermore, the European project METIS enforces vehicles to transmit small packets with 99.999% reliability under 5 ms end-to-end delay constraints [23].

The 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE) Release 12 has dealt with D2D communication to address the ever-increasing demands for data traffic. Release 13 elaborates upon the use of LTE D2D in public safety while Release 14 describes the set of communication technologies to enable V2X communications for safety critical services. Here "V2X" is a term that collectively refers to V2V, vehicle-to-infrastructure (V2I), and vehicle-to-pedestrian (V2P). Release 15 covers the support of advanced V2X services (like vehicle platooning, advanced/remote driving, extended sensors) still being backward compatible with Rel-14 V2X (for the delivery of safety messages). The focus of 3GPP Release-16 and beyond is the expansion of the mobile ecosystem to new areas such as 5G URLLC and vehicle communications for autonomous driving use cases (5G Cellular-V2X). Fig. 1 represents several use cases considering D2D and vehicular communication in 5G networks.

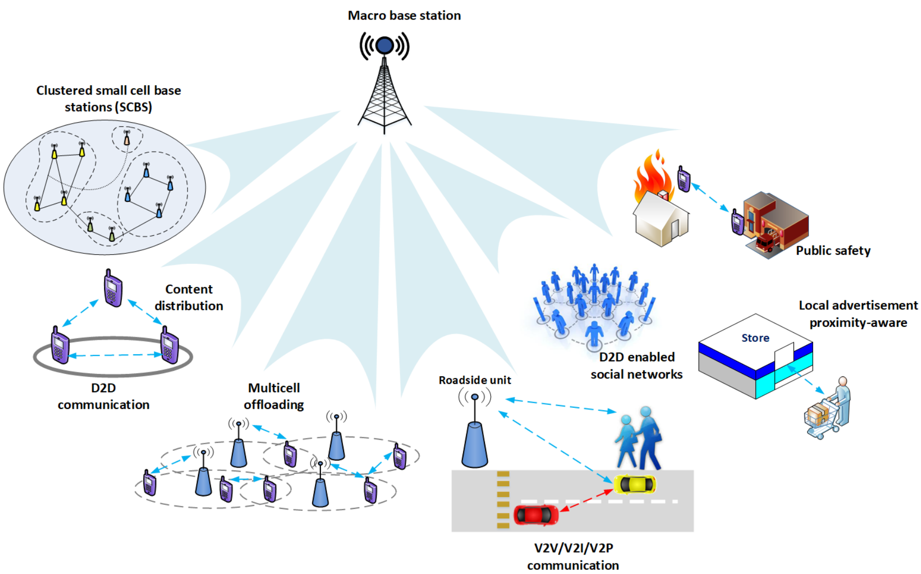

Fig. 1. Use case scenarios in 5G networks.

1.2 Objectives and scope of the thesis

The main objective of this thesis is to provide novel analytical frameworks that bring forward new ideas from matching theory, graph theory, and optimization, to address some of the fundamental challenges of future wireless networks by developing novel, social-aware resource management algorithms and protocols, as well as providing performance analysis for various scenarios in both cellular and local area networks. In particular, this dissertation provides a comprehensive study of the following problems: 1) User association for D2D-enabled cellular network to increase users' QoE and enhance network energy, 2) Leveraging wireless and social networks to improve network capacity and traffic offloading in D2D enabled SCNs, 3) Tractable analysis of joint network formation and QoS-aware resource allocation in V2V networks while exploring spatio-temporal characteristics of vehicles, and 4) RRM for URLLC in V2V networks while capturing both traffic queues and interference.

Specifically, Chapter 3 of this thesis, first, explores the benefits of proximity-aware D2D links to enhance energy and capacity of networks. Load balancing and interference management are crucial in dense SCNs scenario; therefore, Chapter 3 further investigates user association in D2D-enabled SCNs leveraging user's social relationships. Chapter 4, explores the spatio-temporal aspects of vehicular networks to improve resource allocation for V2V networks. Satisfying demanding requirements is vital for safety services in V2V scenarios; therefore, Chapter 4 investigates URLLC-aware resource allocation techniques.

1.3 Contributions of the thesis

The author's research work at the University of Oulu was published in two journal papers [IV, VI] and four conference papers [III, I, II, V]. The author of the thesis was involved in all the steps from the main idea to the final production of results which involved investigated original ideas, mathematical modeling, deriving equations, simulation and producing numerical results, evaluating the performance metrics, and writing technical papers. The co-authors provided valuable comments, criticism on ideas, editorial comments, and guidance during the process. The main contributions of this thesis are listed as follows and summarized in Fig. 2:

1. Architectural framework and performance evaluation of D2D enabled mobile cloud (Paper III).
2. User association in D2D enabled SCN for multi-cell scenarios exploiting social-ties among D2D UEs (Paper I, IV).
3. Analysis of novel proximity and load-aware resource allocation for V2V communication (Paper II).

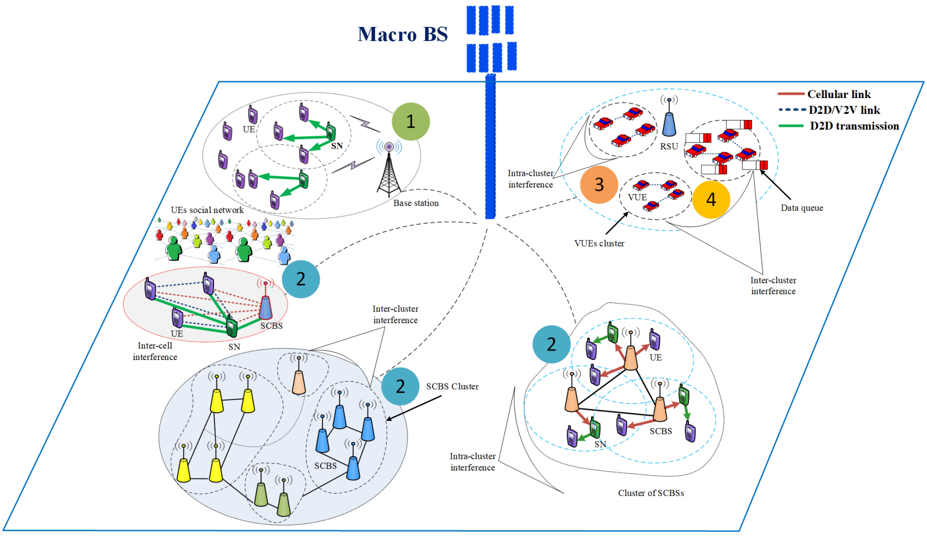

Fig. 2. D2D and V2V communication approaches in the thesis

4. Performance analysis of latency- and reliability-aware resource allocation for V2V communication (Paper V, VI).

Paper [III] introduces the concept, and architectural framework of D2D enabled mobile cloud for resource sharing. The proposed system exploits short-range links to establish a cluster-based network between nearby devices which adapts according to the environment using various cooperation strategies. A novel architecture of mobile cloud is proposed, in which the total coverage area of a BS is divided into several logical regions (clusters). User equipments (UEs) are classified into a primary cluster head (PCH), secondary cluster head (SCH) and standard UEs (UEs). A selected PCH and SCH manage each cluster. An algorithm is proposed for the selection of PCH and SCH based on signal-to-interference-plus-noise (SINR) and residual energy of UEs. Finally, each PCH and SCH distributes data in their respective regions via D2D links.

In paper [I], a novel social network aware solution is proposed for user association in D2D enabled wireless SCNs. The proposed approach exploits the social relationships between UEs and their physical proximity to optimize network throughput. A matching game is formulated between UEs and their serving nodes (SNs). In the proposed game, the SN is a SCBS or an important node with D2D capabilities. In this game, the SCBSs and UEs maximize their utility functions capturing both the spatial and social structures of the network. This work mainly focuses on un-coordinated SCBSs scenario. Paper

[IV] continues the work in [I] by extending the system to the coordinated scenario case. Due to the combinatorial nature of the network-wide UE-SN matching per SCBS, the problem is decomposed into a dynamic clustering problem in which SCBSs are grouped into disjoint clusters based on mutual interference. Subsequently, a UE-SN matching game is carried out per cluster. The game under consideration is shown to belong to a class of matching games with externalities arising from interference and peer effects due to users' social distance, enabling UEs and SNs to interact with one another until reaching a stable matching.

Paper [II] proposes a novel proximity and load-aware resource allocation scheme for V2V communication. The proposed approach exploits the spatio-temporal traffic patterns, in terms of load and vehicles' physical proximity. The objective of this work is to minimize the total network cost, which captures the tradeoffs between load (i.e., service delay) and successful transmissions while satisfying vehicles' QoS requirements. To solve the optimization problem under slowly varying channels, the main problem split into two interrelated sub-problems. First, a dynamic clustering mechanism is proposed to group vehicles in clusters based on their traffic patterns and proximity information. Second, a matching game is proposed to allocate resources for each V2V pair within each cluster. The problem is cast as many-to-one matching game in which V2V pairs and resource blocks (RBs) rank one another to minimize their service delay.

Paper [V] proposed proximity and QoS-aware resource allocation scheme for V2V communication. The proposed approach exploits the spatial-temporal aspects of vehicles in terms of their physical proximity and traffic demands, to minimize the total transmission power while considering queuing latency and reliability. Paper [VI] continues the work started in [V] by extending the work to dynamic resource allocation subject to URLLC requirements for the vehicular network. Leveraging the spatial and temporal nature of V2V communication, VUEs are grouped into dynamic clusters instead of a fixed number of clusters. A novel algorithm is proposed based on matching theory for dynamic allocation of RBs to VUEs inside each cluster. Furthermore, a method is proposed for interference estimation based on the history of VUEs traffic demand and their geographical information. Finally, a latency- and reliability-aware power allocation solution is proposed for each VUE pair over the assigned subset of RBs. Extensive simulations have been performed to analyze the performance of the proposed approach as compared to the state-of-the-art.

The author of this thesis also contributed in many works, which are not part of this thesis including, D2D-enabled mobile cloud [24, 25], user association in millimeter wave SCN [26], extending D2D for vehicular communication [18], latency minimization for 5G fog-network [27] and time synchronization issues for URLLC [28].

1.3.1 Organization of the thesis

This thesis is organized as follows: Chapter 1 present the research topics and research scope, as well as a summary of the thesis. In Chapter 2, presents a state-of-the-art review of the research topics covered in this thesis. The research topics include D2D communication, D2D enabled SCNs, V2V communication, and its inherent challenges are discussed. In Chapter 3, the main research contributions on D2D communication and D2D enabled SCNs based on original research publications are summarized, followed by the significance of the contributions, main findings, and key results. Chapter 4 concentrates on V2V communication, summarizes the original articles, and highlights the primary targets, limitations, and key results of the papers that are part of the thesis. Finally, the conclusions and discussion of future research are presented in Chapter 5.

2 State of the art

In this chapter, state of the art within the scope of this thesis is discussed. This chapter is divided into two main sections. The first section provides an overview, challenges related to D2D enabled SCNs. The second section discusses the utilization and benefits of D2D short-range links for V2V communications. Furthermore, an overview and the challenges related to V2V communication are identified.

2.1 D2D enabled SCNs

The increasing need for wireless capacity mandates novel cellular architectures for cost-effective delivery of high QoS. Small cell networks, also known as heterogeneous networks (HetNets), have attracted considerable attention from the research community. Small cells include micro, pico, and femto cells. SCNs, built on the premise of deploying inexpensive, low-power small SCBSs to boost wireless capacity and offload traffic [29]. The main goal of small cells is to increase capacity and offload the macro network.

Small cells were introduced in 3GPP Release 8, for network densification. The key motivation of using low-power SCNs is to bring user and BSs closer to each other. The deployment of SCNs results in enhancing data rates, battery life, transmission power, and coverage. Furthermore, deploying SCNs in low-coverage areas of macro cells helps to offload traffic from macro cells and therefore increase network capacity. Leveraging the self-organization capabilities of SCNs reduces effort and cost of maintenance by providing ease of deployment. Additionally, the capacity scale linearly increases with the increasing number of cells. However, SCNs alone will not able to satisfy the growing demands of mobile data traffic [2], which has led to the emergence of new technologies, as discussed in the following.

One of the key enabling technologies to increase spectral efficiency and decrease the transmission delay is to allow mobile devices to communicate with one another directly. *Device-to-device (D2D)* communications refer to direct communication between two geographically co-located wireless devices over short-range links without the involvement of the core network infrastructure (i.e., BS). D2D communication is an effective technology to enable many new use cases including proximity-based services [30], traffic offloading [31], multi-hop relaying [32], public safety services [33, 34, 35], vehicular communication [36] and many more [37]. Social networks such as Tinder, Waze, and Facebook are possible examples of proximity and social-aware D2D communications. Many benefits of D2D communication include improved QoE of cell-edge users, traffic offloading, low latency communications, and coverage expansion, among others [38, 39, 40, 41].

In conjunction with SCNs, D2D communication over cellular bands has emerged as a promising technique to further improve the performance of SCNs. Nonetheless, D2D links may interfere with cellular transmission, and therefore, proper resource management is required. However, most of the RRM work on SCNs and D2D rely on conventional physical layer metrics such as CSI to optimize network performance [42]. The modern handheld devices are capable of providing diverse useful contextual information such as location, social ties, trajectory, and common interests of the users [43, 44]. For example, in a football stadium, a group of neighboring friends may like to share the statistics of a player. Coupled with their physical proximity, the social networking relationships between these users can indicate their common interests to share the same content. In a conventional setting, a SCBS often ends up serving different users with the same content using multiple duplicate transmissions, which leads to a waste of resources and degrades the overall QoS. Social network-aware user association, as presented in this thesis, is a new paradigm to boost the performance of SCNs by exploiting D2D communications.

To this end, one promising approach to address the resource management and scheduling problems is to incorporate social information together with network connectivity to further boost the network performance. Therefore, novel networking protocols for resource management exploiting social network information must be developed for D2D-enabled cellular networks[10].

2.1.1 Classifications of D2D networks

Based on the spectrum usage for direct communication between devices, D2D communications are classified in the following categories, as illustrated in Fig. 3.

– **In-band communication:** D2D users use the cellular spectrum for communication. As the operators typically own the spectrum, a BS manages the D2D links while ensuring communication performance.

  In-band communication is further divided into two sub-categories.

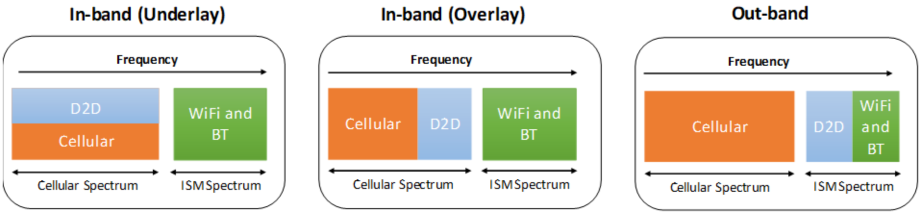

Fig. 3. Classification of D2D communication in cellular networks

- *Underlay in-band D2D*, in which the same frequency band is used for D2D and cellular users. To mitigate interference, careful resource management is required to increase spectrum efficiency and thus is one of the main focus of this thesis.
- *Overlay in-band D2D*, where a dedicated frequency band (dedicated mode) is used for D2D and cellular users. Although interference is mitigated by having a dedicated band for cellular and D2D communication, which may result in the underutilization of the frequency resources.

– **Out-band:** D2D links exploit the unlicensed spectrum. Although the out-band approach avoids D2D communications interfering with cellular communication. However, due to the uncontrolled nature of the unlicensed spectrum, D2D communication may suffer from interference.

2.1.2 Challenges in D2D enabled SCN

The benefits of D2D communication are accompanied with a number of technical challenges that include proximity service discovery (ProSe), resource allocation, and inter-cell interference coordination between cellular and D2D links [8, 9, 10].

Device discovery: Device discovery can be made employing asynchronous scan/search mechanisms using beacon sequences. A periodical peer broadcast searching mechanism is used to identify users in proximity and setting-up D2D communications. Device discovery is one of the major challenges in D2D communication, as a device needs to determine the presence of other devices, information about offered services and satisfy the proximity conditions, before establishing a direct communication path [45, 41, 46].

Resource management: Resource allocation in D2D networks is essential not only to exploit possible frequency diversity among the channels but also to increase the spectral efficiency by proper resource reuse and management. Recently, resource allocation for D2D communication has become a major trend for operators to offload traffic [47, 48, 49]. In particular, RRM is required to manage resources between cellular and D2D or within D2D. In D2D systems, UEs do not necessarily communicate via BS or SCN; instead they communicate directly. This underlying communication generates interference due to the reuse of the same resources of the conventional cellular network. Therefore, efficient interference management techniques are required to keep the interference under control [50, 51, 52, 53, 54]. In this respect, D2D communication for the single and multi-cell scenario provides advantages and complexity to the system. Many works reduce the resource allocation problem complexity by limiting the analysis to a single-cell case, assuming that an advanced inter-cell interference mitigation scheme works on top of the per-cell resource allocation algorithms [48, 49]. Most of the prior mechanisms for D2D have focused on mitigating interference within a single-cell system, and they fail to address inter-cell interference. Exploiting D2D links for reusing spectrum resources in a multi-cell scenario is presented in [55, 56, 57].

User association: SCNs with D2D communications are a promising solution for cost-efficient delivery of high data rates. A key challenge in such D2D-enabled SCN is to design an efficient association scheme with D2D mode selection for load balancing [58, 59, 60]. Therefore, the selection of a preferred SN that can be either SCBS or D2D user plays an important role [24]. In [11], the authors present a protocol for resource allocation and selection of potential D2D SNs to improve the sum rate of D2D links. In [12], an optimization problem is formulated, enabling D2D links to improve their resource utilization and aggregate link capacity. Conventional physical layer metrics have been widely used to optimize the network performance for SCNs, and D2D enabled user association [3, 4, 5, 6, 8, 9, 12].

Even though underlaid in-band D2D communication increases the spectral efficiency, the interference caused by reuse of same frequency resources for D2D and cellular communication degrades the overall system performance. Moreover, UEs are power-limited, which makes energy efficiency a critical issue. Furthermore, an appropriate selection of SN and user association in a dense deployment of D2D-enabled SCNs is challenging due to load balancing and interference from other SCNs.

2.2 V2V communications

The rapid advancement in wireless communication technologies along with the growing number of vehicles have brought new benefits to the automotive industry. Connected vehicle wireless services have existed for more than a decade with the provision of automated crash notifications, vehicle breakdown notifications, traffic information, and infotainment services, among others. V2V communication is the transmission of data between vehicles through a wireless medium. This data includes the vehicle's position, speed, the direction of travel, loss of stability, and braking (referred to as the *basic safety message*). Cellular systems were initially designed for mobile broadband traffic and did not take into account the dynamic nature of the vehicular network. Many works have been presented in the literature to show the suitability of cellular communications for vehicular applications [17, 16]. Although LTE can meet specific requirements for C-ITS applications with low traffic-load, it is unable to address several deficiencies in a wide variety of use cases, as:

- Ensuring traffic safety for the use cases, when the vehicles are out of coverage of the BS such as in a tunnel, underground parking spots, and so on.
- Network scalability, unbound delay, lack of reliability, and varying QoS.
- Usually, global CSI is required at all network entities, which is impractical for vehicular networks.

V2V communications is possible over the existing LTE Uu interface employing 3GPP Release 13. On the other hand, the low latency communication and the support for very high load scenarios may only be feasible using the direct mode via PC5 interface. The direct mode, based on Release 12 ProSe D2D for public safety, was completely redesigned to support V2V communication more efficiently. The automobile industry, for instance, sees two main trends with relevance to the 5G automotive vision: (1) automated driving and (2) road safety and traffic efficiency services. These trends are particularly relevant to many of the features discussed in 3GPP Release 14 [20]. 3GPP defines two configurations for scheduling and interference management of V2V traffic [61, 62]: i) *Configuration 1* (referred to as Mode 4) based on a distributed algorithm for sensing with semi-persistent transmission between vehicles over *PC5 interface*, ii) *Configuration 2* (referred to as Mode 3), is a centralized approach, driven by a BS to allocate V2V resources using control signaling over *Uu Interface*.

2.2.1 Classification of vehicular communications

Any communication technology involving a vehicle as a source or destination of a message is referred to as vehicular communication. In this context, a cooperative intelligent transportation system (C-ITS) assumes a set of communication technologies

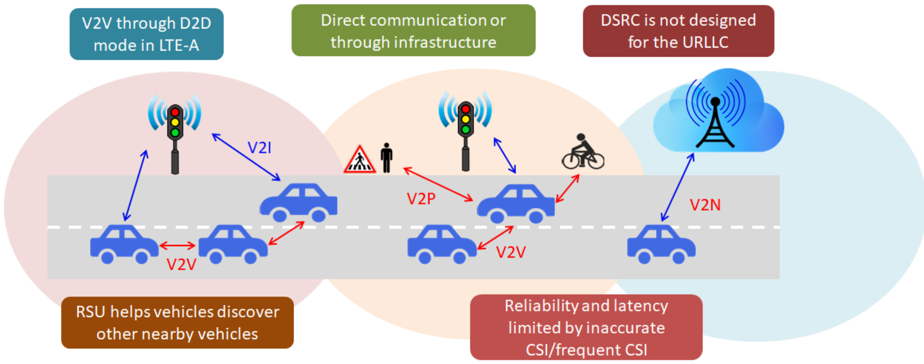

Fig. 4. Types of V2X applications support in 3GPP

to enable V2X. Depending on the nature of the communication and endpoint, several scenarios of V2X communications are considered as depicted in Fig. 4.

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

Two major standardized technologies are currently considered for wireless access in V2X communications: short-range ad-hoc communication technology via the IEEE 802.11p standard [63] and cellular network via the 3GPP LTE standard. Furthermore, these standards are mostly utilized in vehicular on-board units (OBUs) and roadside units (RSUs) such as traffic signals which are typically fixed with transport infrastructure. In terms of availability, IEEE 802.11p has the desirable features of not relying on any network infrastructure (other than for security management and Internet access) and being fully distributed. Therefore, it does not pose any a traffic bottleneck or single point of failure, as is the case with an infrastructure-based approach such as LTE.

On the other hand, pure ad-hoc topology with uncoordinated channel access strategy used by 802.11p is unable to fulfill the (deterministic) latency, reliability, low spectral efficiency, and capacity requirements of future V2X use cases [64, 65]. These requirements may be achieved utilizing a coordinated channel access strategy (i.e., involving a scheduler) and with admission control. Given the diverse performance requirements from the wide spectrum of vehicular communication, 5G can be an emerging solution for V2X communication. It has been envisioned to exploit the existing

5G infrastructure to support vehicular networking applications through advanced 5G-enabled onboard radios (5G OBRs) connectivity. However, the key challenges are to deliver time-critical data and efficient resource management over the 5G interface. To this end, ultra-reliable and low latency requirements are an essential part of the next generation vehicular networks, and as one of the most challenging applications of 5G, as it requires URLLC for safety-critical use cases and high data rates in many scenarios [66, 67]. This thesis investigates the use of cellular V2V links for supporting safety-related applications, with a focus on URLLC.

2.2.2 Challenges in V2V

V2V is considered as one of the most challenging applications of 5G, as it requires URLLC for safety-critical use cases [66, 67]. The main challenge is to tackle the dynamic environment due to mobility, such as multi-path fading, doppler effects, and shadowing [68]. The benefits of V2V communication accompanied by their technical challenges such as interference management, RRM, CSI acquisition, and strict URLLC requirements.

RRM: RRM mechanisms must be carefully designed for interference mitigation while satisfying the stringent URLLC requirements [69, 70, 71, 72]. The works [73, 72, 74] model the QoS requirements from the SINR viewpoint, i.e., the achievable SINR is above a threshold value. It is worth noting that guaranteeing the stringent QoS in terms of latency and reliability for URLLC is challenging even in the case, where vehicles are within the coverage of a single RSU. Problems related to resource management for URLLC, such as control overhead, guaranteeing network availability, and resource usage efficiency have been discussed in [75]. Vehicular and D2D networks with a focus on QoS-aware resource management are discussed in [36, 73, 76, 77, 74, 70, 72, 78, 79].

Power allocation in V2V: In 5G systems, V2V communication requires a power control mechanism to manage intra-cell interference caused by V2V links, interference towards cellular links, and to reduce the power consumption of short-range communications. Several works have been published in the literature, which takes into account the power allocation as a critical component in vehicular networks [80, 81, 82, 83].

Channel state information acquisition: Typically, full channel state information (CSI) is assumed for efficient resource management, which is impractical for vehicular networks. Due to the fast-varying channel conditions and topological environments, frequent exchange of local information and control signaling can incur tremendous over-head and leads to a degradation in network performance [17, 36, 71].

Centralized RRM solutions: A centralized heuristic QoS based resource allocation scheme incorporating vehicle locations to solve a sum-rate maximization problem is presented in [36, 73, 71]. Many enhancements are introduced in the autonomous and vehicle specific scheduling modes. An interesting concept is to group vehicles in geographical clusters for resource assignment. The RSU configures such clusters in which the vehicles select the resources [84, 85, 86, 87].

Latency and reliability-aware resource allocation: Efficient RRM techniques are essential to satisfy the stringent URLLC requirements. Dynamic and flexible RRM techniques in V2V networks offer the possibility to adapt to the localized service requirements and, hence, need to be carefully designed. Legacy solutions for V2X communication rely on ad-hoc communication over the IEEE 802.11p standard and backhaul communication over the LTE cellular standard [17]. Nevertheless, due to the dynamic nature of vehicular communication, legacy solutions suffer from several drawbacks such as network scalability, efficient resource management, unbounded delay, lack of reliability guarantees, and varying QoS requirements [13, 65, 36]. On the other hand, the performance of the LTE-based vehicular communication is often unsatisfactory, particularly for URLLC scenarios [16, 36]. Therefore, seeking optimal RRM solutions to enable V2V communication is needed.

The overall end-to-end latency of a communication link contains four parts, i.e., processing latency, propagation latency, transmission latency, and queuing latency [88]. However, most of the existing works have only considered the transmission latency for the V2V links while neglecting the dominant queuing latency. Considering the requirements for reliability and transmission latency of the V2V links, resource allocation schemes have been developed in [36, 73, 72] with and without permitting spectrum sharing among the V2V links. The RSU can assist in scheduling multiple transmissions; however, if performed poorly, V2V communications may cause significant degradation in system performance due to interference. Moreover, guaranteeing the required latency and reliability for V2V communication is demanding. Hence, RRM solutions, including time-frequency resources and transmit power, are a crucial design aspect to enable critical V2V communications.

2.3 Methodologies and tools

Before providing an in-depth discussion for each of the research challenges mentioned above, this section reviews the main tools used in this thesis to solve the problem of resource allocation in D2D-enabled SCNs and V2V communication. Nonetheless, successful integration of various technologies such as dense SBS deployment, D2D, V2V, and others, is contingent upon exploring mathematical tools tailored to their unique characteristics. Graph theory [89] and matching theory [90] are powerful tools to solve the problem of resource management and user association.

2.3.1 Graph theory

The seminal paper by Leohard Euler on "Seven Bridges of Königsberg" in 1736 is regarded as a pioneering work in graph theory. In this paper, a walking problem is solved such that a person would cross each bridge only once [89]. Graph theory is used in many various scientific fields such as physics, biology, social and information systems since many practical problems can be modeled as a graph. Graph theory is likewise regarded as a powerful tool in wireless communication to solve resource management problems.

Network resources can be allocated in a centralized, decentralized, or distributed fashion. In a centralized setting, a central controller is required, which is responsible for RRM. In distributed networks, a node can make a decision based on the information exchange between nodes. The concept of *cluster head* is used in the clustered network, where a cluster head can be interpreted as the best possible node (in terms of energy, data transfer, channel quality, etc.). This thesis utilizes different approaches of graph theory in resource management, particularly in network association and resource allocation problems. Wireless resource management problems have been widely discussed in graph-theoretical literature. Graph coloring approaches are used to dynamically allocate spectrum resources and improve spectrum efficiency [91]. In the case of wireless communication, graph coloring is used to assign different colors for adjacent nodes to avoid interference [92]. A resource allocation problem can be modeled as a bipartite graph, where the objective is to find a vertex-to-vertex (resource-to-user) matching between two disjoint sets of vertices. An RRM approach based on a bipartite graph was proposed in [93], where vehicles and spectrum resources are represented by vertices whereas the edges represent the achievable rate in each resource block based on the SINR that a user perceives.

A graph $\mathcal{G} = (\mathcal{J}, \mathcal{E})$ is represented by a set of vertices $\mathcal{J}$ and a set of edges $\mathcal{E}$. Vertices are the connection points (e.g., node[1]) in the graph and edges are the lines connecting vertices (e.g., communication link between nodes). A graph is usually used to describe a particular relationship between nodes. The degree of a vertex defines the number of edges connected to it.

The connectivity of node j can be represented by an adjacency matrix $\boldsymbol{E}$, which is a $J \times J$ symmetric matrix, where J is the number of nodes in the graph $\mathcal{G}$. The adjacency matrix is expressed as:

$$E_{j\tilde{j}} = \begin{cases} 1, & \text{if there is a edge between node } j \text{ and } \tilde{j}, \\ 0, & \text{otherwise.} \end{cases}$$

One way to identify adjacent nodes is to utilize clustering. This thesis explores the concept of similarity to form clusters of nodes. In particular, in this thesis, social networks are used to solve resource association problems. A social network can be represented as a set of users having social-ties (e.g., based on context) within their proximity range.

Centrality concepts were first developed in social network analysis. In graph theory and network analysis, the indicators of centrality identify the most important vertices within a graph. A node with a high popularity has a high probability of having a link to other network nodes. Hence, social importance can be characterized by having curtail points for data distribution in the network, since it has social ties/links with other nodes in the network. The three most popular ways to quantify the social popularity of nodes in a social graph are degree, closeness, and betweenness centrality [94, 95].

Closeness centrality: The closeness centrality is a measure of similarity between a pair of nodes. The degree of similarity can be measured by the ratio of common neighbors between individuals in a social network. The degree of similarity between nodes j and $\tilde{j}$ has an essential effect in terms of data dissemination. Nodes having a lower degree of similarity are good candidates for data dissemination [96]. Let $\boldsymbol{Q}$ be a $J \times J$ similarity matrix, such that a pair of nodes $(j, \tilde{j})$, depending on whether they are connected directly or indirectly, their corresponding similarity measuring element $q_{j\tilde{j}}$ of $\boldsymbol{Q}$ is defined as [96]:

$$q_{j\tilde{j}} = \begin{cases} \sum_{\hat{j} \in v(j) \cap v(\tilde{j})} \frac{1}{t(\hat{j})}, & \text{if } j, \tilde{j} \text{ are connected,} \\ 0, & \text{otherwise,} \end{cases} \tag{1}$$

[1] A node can be a UE/vehicle or BS.

where $\nu(j)$ is the set of neighbors of j, $\hat{j} \in \nu(j) \cap \nu(\tilde{j})$ are the common neighbors of nodes j and $\tilde{j}$, and $t(\hat{j})$ is the degree of UE $\hat{j}$. A simple additive weighting (SAW) method is used to normalize the similarity matrix, in which the normalized value of each element $q_{j\tilde{j}}$ of $\boldsymbol{Q}$ is:

$$s_{j\tilde{j}} = q_{j,\tilde{j}}/q_{\tilde{j}}^{\max} \ \ \forall j,\tilde{j}, \tag{2}$$

where $q_{\tilde{j}}^{\max} = \max_j q_{j\tilde{j}}$. Consequently, we obtain the normalized similarity matrix $\boldsymbol{S}$ of dimension $J \times J$, where the jth row and $\tilde{j}$th column of $\boldsymbol{S}$, i.e., $s_{j\tilde{j}}$ denotes the normalized similarity between nodes j and $\tilde{j}$.

Edge betweenness centrality: Edge betweenness centrality is based on the idea that an edge becomes central to a graph if it lies between many other nodes, i.e., it is traversed by many of the shortest paths connecting a pair of nodes [95]. Edges with a high betweenness centrality are considered important because they control information flow in the social network. Let $\boldsymbol{A}$ be $J \times J$ edge betweenness centrality matrix, where element $a_{j\tilde{j}}$ is the edge betweenness centrality of the link between nodes j and $\tilde{j}$. The betweenness centrality $a_{j\tilde{j}}$ of an edge $e \in \mathcal{E}$ [94] between nodes $(j,\tilde{j})$ is the sum of the fraction of all pairs' shortest paths that pass through edge e. The normalized $a_{j\tilde{j}}$ is:

$$a_{j\tilde{j}} = \frac{\sum\limits_{j,\tilde{j} \in \mathcal{J}} \dfrac{\gamma(j,\tilde{j}|e)}{\gamma(j,\tilde{j})}}{(J-1)(J-1)}, \tag{3}$$

where J is the number of nodes, the summation $\gamma(j,\tilde{j})$ is over the number of shortest $(j\tilde{j})$-paths, and $\gamma(j,\tilde{j}|e)$ is the number of those paths that traverse edge e.

Similarity graphs: The main objective of similarity is to model the local neighborhood relationships between nodes. There are several ways to find similarities between nodes in graph [97]: 1) In case of *ε-neighborhood graph*, nodes are connected if their pairwise distances are small than ε, 2) In *k-nearest neighbor graph*, connect node j and j' if j' is among the k-nearest neighbor of j, 3) *Fully connected graph*, represents the local neighbor relationships of the nodes, such that the construction is only useful if the similarity function itself models the local neighborhood. An example of a similarity function is a Gaussian similarity function between two nodes with their locations $\boldsymbol{v}_j$ and $\boldsymbol{v}'_j$ is [97]:

$$s^d_{jj'} = \exp\left(\frac{-||\boldsymbol{v}_j - \boldsymbol{v}_{j'}||^2}{2\sigma_d^2}\right), \tag{4}$$

where σ_d controls the impact of neighborhood size. All graphs mentioned above are regularly used in spectral clustering [97]. Spectral clustering exploits both connectivity and compactness of nodes in a graph based on similarity to form clusters in the network.

In this thesis, an adjacency matrix is used to mitigate interference and perform resource allocations. There are numerous aspects which impact interference between nodes. This thesis utilized the notion of physical distance separation and traffic conditions between nodes to find similarities. This idea mitigates the interference and increases spectral efficiency.

2.3.2 Matching theory

Matching theory is a mathematical framework in economics and applied mathematics to study the formation of mutually beneficial relationships and in particular to solve assignment problems. Matching theory is a Nobel-prize winning framework that provides mathematically tractable solutions for the combinatorial problem of matching players in distinct sets. In the wireless communication literature, matching theory has recently become attractive to solve resource allocation problems due to exhibiting useful properties, as discussed in the following: The fundamental wireless resource management problem can be modeled as a matching problem between resources and users. Based on the scenario, the resources can be BSs, time-frequency, chunks, power, or others. The user can be devices, vehicles, stations, or applications. The prime goal of matching is to optimally match resources to the users while taking in to account the constraints of the wireless network. Key components and terminologies of matching problem for wireless resource allocation are as follows:

Sets of players: Two distinct sets of players define the matching problem. Matching problem η assign the players in one set to the player (resource $r \in \mathcal{R}$) of the other set (users $m \in \mathcal{M}$). Let's denote $\eta(m) \subseteq \mathcal{R}$ be the set of all resources allocated to the user m and $\eta(r) \subseteq \mathcal{M}$ represents the set of all users that are assigned to resource r.

Quota: In the matching settings, each player has a quota that specifies the maximum number of players with which it can be matched. Let x_m and x_r be the quota of user m and resource r, respectively, such that $|\eta(m)| \leq x_m|$ and $|\eta(r)| \leq x_r$.

Preference relation and strategy: A preference relation $\succ$ is defined as a reflective, complete and transitive binary relationship between players in $\mathcal{M}$ and $\mathcal{R}$. When building preference relations each user (resource) builds a ranking (i.e., strategy) of the resource (users) using a preference relation. Let $\succ_m$ denotes preference relation of user m and

$U_m(r)$ be the utility of user m over resource r. Given that, $r_1 \succ_m r_2$ if and only if $U_m(r_1) \geq U_m(r_2)$.

Utility function: Utility function is defined to determines the utilities each player assigns over the players of the other set. For specific resource-user matching, the utility function U quantifies certain QoS in the wireless network. Let $U_m(\cdot)$ denotes the objective function of user m as m tries to be matched to resource r that maximizes its utility.

Solution of matching problem: Let's denote $(m,r) \in \eta$ if m and r are matched, and $(m,r) \notin \eta$ otherwise. The solution of the matching problem is a function $\eta : \mathcal{M} \longrightarrow \mathcal{R}$, given that 1) $\forall m \in \mathcal{M}, \eta(m) \subseteq \mathcal{R}$ and $|\eta(m)| \subseteq x_m$, 2) $\forall r \in \mathcal{R}, \eta(r) \subseteq \mathcal{M}$ and $\eta(r) \leq x_r$, and 3) $r \in \eta(r)$ if and only if $m \in \eta(r)$.

Stability of matching solution: The basic solution concept for a matching problem is the so-called two-sided stable matching, if and only if there is no blocking pair. Lets consider $(m,r) \notin \eta$, such that $m' \in \eta(r), m \succ_r m'$ and $\exists m' \in \eta(r), m \succ_r m'$ and $\exists r' \in \eta(m), r \succ_m r'$, then m and r can block the matching η by leaving their current assigned player, r' and m', and creating a new matched pair (m,r).

The classical classification of the matching problems is based on the quotas of the players. In *one-to-one* matching, the quota of all players is equal to one. If at least one player can be matched to multiple players from the opposite sets, while in the other set every player have quota set to one is called *many-to-one* matching problem. Finally, in *many-to-many* matching, at least one player in each set could be matched to more than one member in the other set (e.g., quota is greater than one). For one-to-one and many-to-one matching problems, Gale and Shapely proposed a *deferred acceptance* (DA) algorithm, which always guaranteed to converge to a two-sided stable matching [90].

Based on the wireless-orientation, matching problems are classified into three classes [98]: 1) Canonical matching, 2) Matching with externalities, 3) Matching with dynamics. The matching classification is illustrated in Fig. 5. Canonical matching is the baseline class, in which the preferences of players are fixed and do not vary with in the timeframe of the resource allocation. In class II, the preferences of players are interdependent. Player's may changes their strategies (e.g., based on interference) within the timeframe of resource matching. For matching with dynamic class, the strategy of players in the current resource matching may depend on the strategy in the previous resource matching.

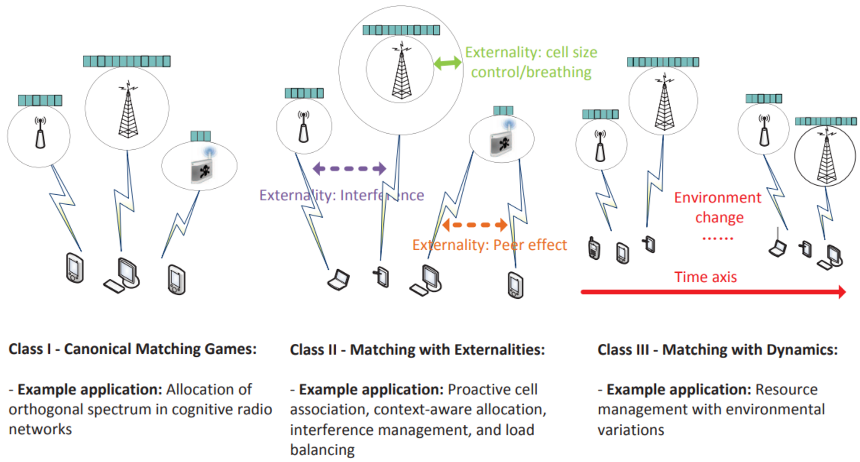

Fig. 5. Wireless-oriented classification of matching problems ([98]©2015 IEEE).

3 User association in D2D

As indicated in Section 2.1.2, D2D-enabled SCNs require selection of a preferred SN and effective user association mechanism to enhance the network capacity. In the dense deployment of D2D-enabled SCNs, user association techniques need to be carefully designed to mitigate inter- and intra-cell interference resulting from the underlaid in-band D2D. Additionally, load-balancing and scheduling become challenging. In this Chapter, Section 3.1 presents solutions for the selection of the preferred SN for a D2D enabled cellular network. Section 3.2 describes a framework for the social-aware user association in D2D enabled SCNs.

3.1 D2D enabled mobile cloud (Paper [III])

In paper [III], a D2D enabled mobile cloud (MC) architecture is proposed. The proposed system exploits the short-range links to establish a cluster-based network between the nearby devices, adapts according to the environment and uses various cooperation strategies to obtain efficient utilization of resources. D2D enabled mobile cloud is a very flexible platform for sharing resources (e.g., bandwidth, energy, etc.) efficiently in a wireless network. By applying D2D enabled mobile cloud in the network, mobile data operators can see the gain in two areas: a) high bit rates and low energy consumption due to proximity gain, b) the reuse gain implies that radio resources may be simultaneously used by cellular as well as D2D links.

There are many applications for such mobile cloud-based architecture, but mobile data offloading is one of the most prominent ones, especially for ultra-dense wireless networks. The proposed system exploits the short-range links to establish a cluster-based network between nearby devices, adapts according to the environment and uses various cooperation strategies to obtain efficient utilization of resources. This thesis proposes a novel architecture of mobile cloud in which the total coverage area of a BS is divided into several logical regions (clusters). Furthermore, UEs in the cluster are classified into primary cluster head (PCH), secondary cluster head (SCH), and standard UEs (UEs).

A PCH can be considered as the cluster head, and has the following responsibilities in the network. 1) exchanges data with other SCHs, 2) radio resource management of MC. The primary function of SCH is to distribute the data locally and with other SCHs and PCH. Selected PCH and SCH manage their cluster. An algorithm is proposed for

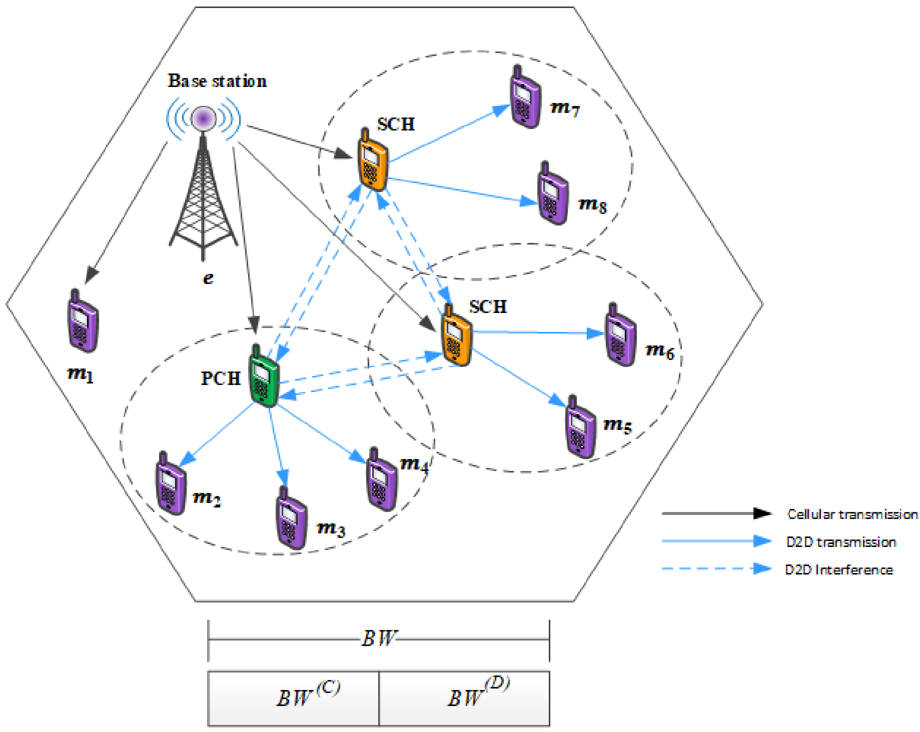

Fig. 6. System model for D2D-enabled mobile cloud ([III]©2016 IEEE).

the selection of PCH and SCH, based on signal-to-interference-plus-noise (SINR) and residual energy of UEs. Finally, each PCH and SCH distributes data in their respective regions by utilizing D2D links.

3.1.1 System model

Consider the *downlink* transmission of a macro-cellular network underlaid by a set of BSs $\mathcal{E}$ and a set of UEs $\mathcal{M}$. Let $\mathcal{A}_e$ be the set of anchor nodes under the coverage of e BS. Here an anchor node represents PCH or SCH. Let $\mathcal{L}_e$ and $\mathcal{L}_a$ be the set of UEs under the coverage of BS e and anchor node a, respectively. An anchor node can be either PCH or SCH under the coverage of the same BS e. A PCH node n is assumed for the given D2D enabled MC. It is assumed that the total bandwidth BW is divided into two equal parts cellular bandwidth $BW^{(C)}$ and D2D bandwidth $BW^{(D)}$. The network model considered for the D2D enabled MC is shown in Figure 6. The achievable rate for cellular *downlink* between BS e and UE $m \in \{\mathcal{A}_e \cup \mathcal{L}_e\}$ is given by:

$$R_{em}^{(C)} = \frac{BW^{(C)}}{|\mathcal{L}_e|} \cdot \log_2\left(1 + \frac{p_e|h_{em}|^2}{\sum_{e' \in \mathcal{E}\setminus\{e\}} p_{e'}|h_{e'm}|^2 + N_0}\right), \tag{5}$$

where p_e is the transmission power of BS e, $|h_{em}|^2$ is the channel gain from BS e to UE m, respectively, while N_0 is the noise spectral density. The interference term in the denominator represents the aggregate interference at UE m caused by the transmissions of other BSs $e' \in \mathcal{E} \setminus \{e\}$. For D2D transmission, interference comes from other anchor nodes (same cell and other cells), hence the rate for D2D downlink between anchor node $a \in \mathcal{A}_e$ and UE $m \in \mathcal{L}_a$ is:

$$R_{am}^{(D)} = \frac{BW^{(D)}}{|\mathcal{L}_a|} \cdot \log_2\left(1 + \frac{p_a|h_{am}|^2}{I_{\mathcal{A}_e} + I_{\mathcal{A}_{e'}} + N_0}\right). \tag{6}$$

The interference term in the denominator represents the aggregate interference at UE m caused by the transmissions of anchor nodes in the same cell $I_{\mathcal{A}_e} = \sum_{a' \in \mathcal{A}_e\setminus\{a\}} p_{a'}|h_{a',m}|^2$ and anchor nodes of other cells $I_{\mathcal{A}_{e'}} = \sum_{\forall e' \in \mathcal{E}\setminus\{e\}} \sum_{\forall \hat{a} \in \mathcal{A}_{e'}} h_{\hat{a}m}$, where p_a is the transmission power of anchor node a, $|h_{am}|^2$ is the channel from anchor node a to UE $m \in \mathcal{L}_a$, respectively.

3.1.2 Metric computation

In this section, a metric is defined for PCH and SCHs selection. The metric depends on residual energy, power used for transmission, and SINR. A high metric value increases the probability of a UE to be selected as PCH or SCH. The metric z_m for a UE $m \in \mathcal{M}$ is defined as:

$$z_m = \frac{\Psi_m}{\Psi_m^{(C)} + \Psi_m^{(D)}}, \tag{7}$$

where Ψ_m is the residual energy of m^{th} UE, and $\Psi_m^{(C/S)}$ is the consumed energy per bit for cellular and D2D communications, respectively. The energy consumed per bit to serve UE m is the ratio between the power consumed per bit $p_{\hat{m}}^{(C/S)}, \hat{m} \in \{\mathcal{E} \cup \mathcal{A}\}$ to the bit rate of the link $R_{\hat{m}m}^{(C/S)}$ for cellular and D2D short-range links, given by:

$$\Psi_m^{(C/D)} = \frac{p_{\hat{m}}^{(C/D)}}{R_{\hat{m}m}^{(C/D)}}, \tag{8}$$

By inserting the values of (5, 6 and 8) in (7):

$$z_m = \frac{\Psi_m R_{\hat{m}m}^{(C)} R_{\hat{m}m}^{(D)}}{R_{\hat{m}m}^{(D)} p_{\hat{m}}^{(C)} + R_{\hat{m}m}^{(C)} p_m^{(D)}}, \tag{9}$$

Moreover, the energy efficiency (EE), is defined as ratio of the total transmitted bits per unit energy consumed (i.e., bits/Joule) given by [99]:

$$EE^{(C/D)} = \frac{R_{\hat{m}m}^{(C/D)}}{p_{\hat{m}}^{(C/D)}}. \tag{10}$$

3.1.3 Main results

A single macro-cell with single sector hexagonal structure is considered, in which UEs are uniformly distributed with no power control. For simulations, one PCH and multiple SCH nodes in the network are assumed. Each UE determines neighbors within a cluster radius of 20 m. System bandwidth of 5 MHz at carrier frequency of 5 GHz is assumed. A single macro sector structure is considered, in which UEs are uniformly distributed over the area of interest. Power is uniformly divided among UEs. For simulations, only one PCH and multiple SCH nodes are considered in the network. Each UE determines its neighbors based on the cluster radius. For the classical baseline scheme, it is assumed that the bandwidth is equally divided among the UEs and achievable data rate at each UE is calculated with respect to the BS. In the proposed scheme, the bandwidth is divided into two equal parts. The first part of the bandwidth is used for cellular communication which is further divided equally between the PCH and SCHs. The PCH and SCHs utilize remaining bandwidth locally by dividing it equally between UEs in their respective regions. The detailed list of parameters assumed for simulations are listed in [III].

Figure 7 shows the cumulative density function (CDF) of UE's data rate for different density of UEs. It can be shown from the figure that there is an increase in the UE data rate relative to the classical approach. The proposed approach yields significant performance gain and achieves almost two times data rate per UE as compared to classical approach. This is due to fact, that proposed approach exploits short-range D2D links for data transmission.

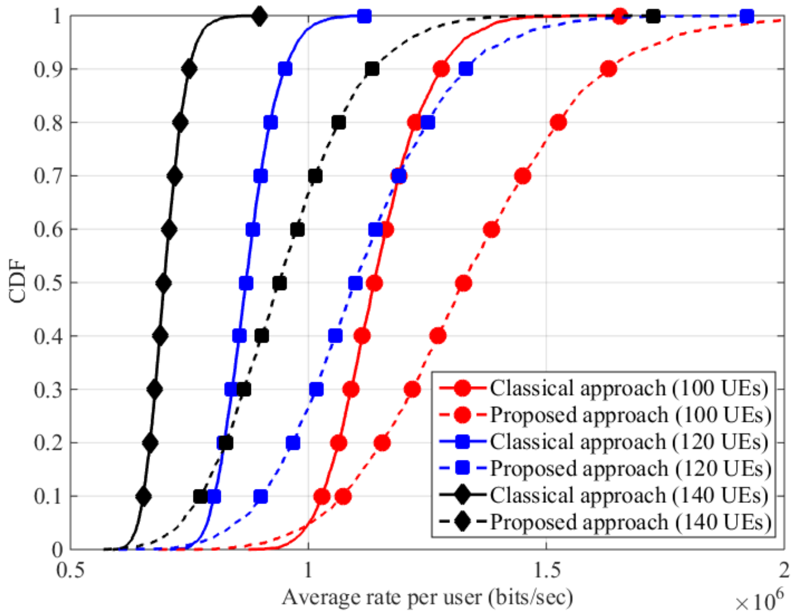

Fig. 7. Data rate comparison for cellular and proposed D2D enabled mobile cloud scheme ([III]©2016 IEEE).

3.2 Social-aware user association in D2D enabled SCNs (Papers [I, IV])

In order to establish D2D links, some UEs can be selected as important nodes to serve other UEs within proximity. For instance, in the context of content sharing leveraging users' social ties allows the SCBS to avoid sending multiple copies of the same content. Instead, by selecting socially important nodes as caching points, UEs communicate via D2D links within the same social network, thereby offloading the BS [100, 101, 102].

The authors in [103] propose a self-organizing cluster-based load balancing scheme for traffic offloading while, the authors in [104] propose a decentralized coordination mechanism with a focus on cell edge users based on system level simulations. However, while interesting, these works are limited to conventional wireless systems relying on a central controller which can cause significant information exchange, and thus will not be appropriate for dense SCNs. This emphasizes the need for decentralized and self-organizing resource management solutions. A physical and social relationship between D2D nodes is used to analyzed the effect of interference on coverage probability

[105]. In contrast, there is a need to adopt a more holistic view for the social context by basing it on other social dimensions such as the actual interactions between users. The work described in [106, 107, 108, 109, 110, 111, 112] has further explored the user social metrics for resource management.

One of the primary objectives of this thesis is to establish the social-aware in-band D2D communication. By exploring the proximity-aware functionality of D2D network, UEs are grouped into clusters to further improve in-band D2D performance [113]. Additionally, UEs can also be clustered based on social aspects of the network [114, 106, 114]. In this way, cluster head/SN can be elected in order to offload the BS traffic to enhance resource utilization [24]. The proximity-aware functionality, social attributes, and content preferences have significant impact on D2D cluster formation [115].

Papers [I, IV] focus on the user association in D2D-enabled SCNs while exploring the social ties among users. This thesis employed a cluster-based approach for flexible user association while exploring user's social ties. A dynamic mechanism is proposed to group locally-coupled SCBSs into clusters based on their location and traffic load. Within each cluster, SCBSs coordinate the user-association by incorporating both physical and social aspects. Therefore, a two-sided matching game is defined in which UEs and SNs act as players. To solve this game, a distributed algorithm is proposed which allows UEs and SNs to self-organize and to maximize their own utilities within their respective clusters. In addition, the proposed algorithm is shown to converge to a stable matching in which no player has an incentive to match to other player, even in the presence of interference and peer effects due to users social ties. Simulation results validate the effectiveness of the proposed approach, and show significant performance gains compared to the baseline social-unaware user association approaches.

3.2.1 Wireless network model

Consider the *downlink* transmission of a macrocell network underlaid by B SCBSs. It is assumed that all SCBSs transmit on the same frequency spectrum (i.e., co-channel deployment) with bandwidth BW. Let $\mathcal{B} = \{1,\dots,B\}$, $\mathcal{M} = \{1,\dots,M\}$, and $\mathcal{I} = \{1, \dots, I\}$, $\mathcal{I} \subset \mathcal{M}$, $\mathcal{I} \neq \mathcal{M}$, be the sets of SCBSs, UEs, and important UEs, respectively. Here, an important UE is defined as a socially well connected node within a confined coverage area serving for D2D communication. Let $\mathcal{S} = \{1,\dots,S\}$ be the set of SNs, which can be either SCBSs or important UEs, i.e., $\mathcal{S} = \mathcal{B} \cup \mathcal{I}$. Let $\mathcal{L}_b$ be the set of UEs

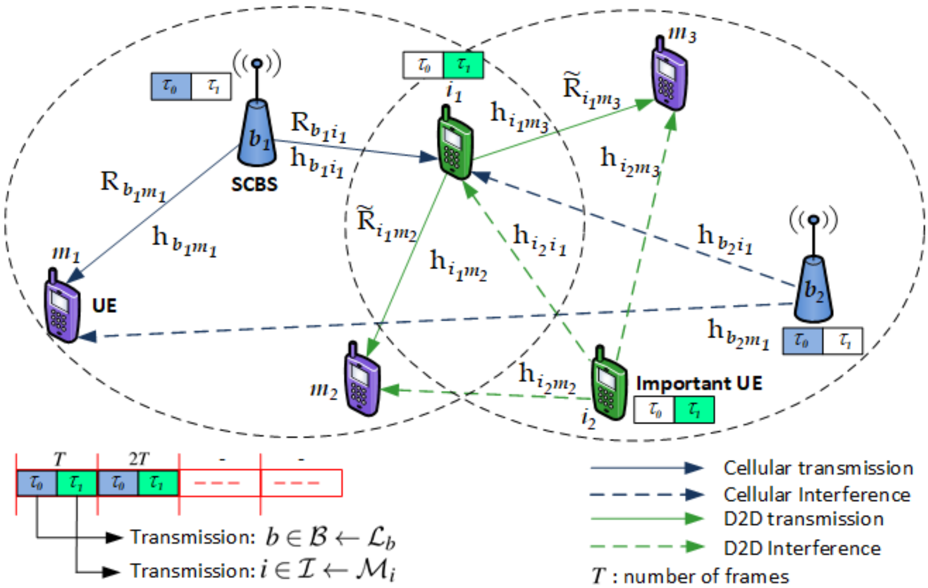

Fig. 8. Network model for D2D-enabled SCNs ([IV]©2017 IEEE).

serviced by SCBS b and $\mathcal{M}_i$ be the set of UEs serviced by the important node $i \in \mathcal{I}$. Let $\mathcal{M}_u$ be the set of M_u non-serving UEs such that, $\mathcal{M} = \mathcal{M}_u \cup \mathcal{I}$. The considered network model is shown in Fig. 8. Lets assume only slowly-varying CSI at the SCBS [116]. Moreover, in the considered model users are not capable of transmitting and receiving simultaneously, so half duplex UEs are considered. In the first time slot τ_0, SCBS b transmits to UE $\hat{m} \in \mathcal{M} \setminus \mathcal{M}_i, \forall i \in \mathcal{I}$ while in the next time slot τ_1, important UE i decodes and forwards its received signal to UE $m \in \mathcal{M}_i$. Thus, the achievable rate between SCBS $b \in \mathcal{B}$ and UE $\hat{m} \in \mathcal{M} \setminus \mathcal{M}_i, \forall i \in \mathcal{I}$ at time slot τ_0 is given by:

$$R_{b\hat{m}} = \frac{\tau_0}{T} \cdot \frac{BW}{|\mathcal{L}_b|} \cdot \log_2\left(1 + \frac{p_b h_{b\hat{m}}}{N_0 + \sum_{b' \in \mathcal{B} \setminus \{b\}} p_{b'} h_{b'\hat{m}}}\right), \tag{11}$$

where T is the time duration for a frame such that $T = \tau_0 + \tau_1$, p_n is the transmission power of SCBS n, $h_{n,\hat{m}}$ is the channel gain from SCBS n to UE $\hat{m}$, respectively, while N_0 is the noise spectral density. The interference term in the denominator represents the aggregate interference at UE $\hat{m}$ caused by the transmissions of other SCBSs $n' \in \mathcal{N} \setminus \{n\}$. It is assumed that the important UE sends (the same) content to all D2D UEs within its vicinity. Therefore, the rate between important UE $i \in \mathcal{I}$ and UE $m \in \mathcal{M}_i$ at time slot τ_1

is given by:

$$R_{im} = \min_{\forall m \in \mathcal{M}_i} \left[\frac{\tau_1}{T} \cdot BW \cdot \log_2 \left(1 + \frac{p_i h_{im}}{N_0 + \sum_{i' \in \mathcal{I} \setminus \{i\}} p_{i'} h_{i'm}} \right) \right], \tag{12}$$

where p_i is the transmission power of important UE i and $h_{i,m}$ is the channel gain from the important UE i to a given UE m, respectively. The interference term in the denominator represents the aggregate interference at UE m caused by the transmissions of other important UEs $i' \in \mathcal{I} \setminus \{i\}$. The achievable rate between SCBS b and D2D UE $m \in \mathcal{M}_i$ over $T = \tau_0 + \tau_1$ is:

$$\widetilde{R}_{bm} = \min(R_{bi}, R_{im}). \tag{13}$$

3.2.2 Social network model for UEs

The social network can be defined by a weighted graph whose vertices represent nodes and edges represent their relationships strength based on parameters such as friendship or common interests. The concept of *social distance* is utilized to measure the strength of a link between two nodes. The social distance $w_{m\tilde{m}}$ is the weight of the edge between UEs m and $\tilde{m}$, and adjacent UEs $(m, \tilde{m})$ are connected via an edge. Let $\boldsymbol{W}$ be a social distance matrix where element $w_{m\tilde{m}} \in [0,1]$ quantifies how the social distance of a user affects its utility which is given as the weighted sum of matrices $\boldsymbol{S}$, $\boldsymbol{A}$ representing respectively the closeness similarity and edge betweenness centrality among UEs:

$$\boldsymbol{W} = \alpha^{SIM} \boldsymbol{S} + \alpha^{EBW} \boldsymbol{A}, \tag{14}$$

where α^{SIM} and α^{EBW} given in (14) are tunable parameters such that $\alpha^{SIM} + \alpha^{EBW} = 1$. The *important UE* selects its preferred peer based on the composite social and physical distance captured by the following weighted cost matrix $\boldsymbol{C}$, where element $c_{m\tilde{m}}$ is given:

$$c_{m\tilde{m}} = (\varepsilon_{m\tilde{m}} w_{m\tilde{m}}) / d_{m\tilde{m}}. \tag{15}$$

In (15), the social distance is combined with the actual physical distance between UEs, where $w_{m\tilde{m}}$ denotes the social distance, $d_{m,\tilde{m}}$ is the Euclidean physical distance between UE m and $\tilde{m}$ and $\varepsilon_{m\tilde{m}}$ is a normalization constant.

3.2.3 Problem formulation

In this section, the problem of SCBSs clustering and flexible user association is studied. This work focuses on issues related to user association while incorporating users' social-ties in the network. First, a framework of matching theory [117] is utilized to develop a distributed and self organizing solution, composed of two steps: 1) cluster SCBSs in terms of mutual interference, 2) a two-sided matching model is studied that enables each cluster to efficiently optimize user association by incorporating both physical and social aspects. Therefore, a two-sided matching game is defined in which UE and SN acts as players. In this game each player tries to match (associate) to the most suitable SN based on its own preference $\eta : \mathcal{M} \longrightarrow \mathcal{S}$. Next, the social-aware utility functions are defined which capture both wireless and social network metrics in order to optimize the user association mechanism.

UE and SN utilities

The utility of a given UE is defined as the achievable rate taking into account the interference from adjacent SCBSs and important UEs. The achievable rate between SN $s \in \mathcal{S}$ (important UE or SCBS) and UE $m \in \mathcal{M}$ for a given matching η is:

$$U_{sm}(R_{sm}, w_{sm}, \eta) = \begin{cases} R_{sm} + \sum\limits_{\tilde{m} \in \mathcal{M} \setminus m} \dfrac{\widetilde{R}_{m\tilde{m}}}{1 - w_{m\tilde{m}}} e_{m\tilde{m}}, & (s = n \text{ and } m = i), \\ R_{sm}, & \text{if } m \text{ connected to SN } s \ (s = b), \\ \widetilde{R}_{sm}, & \text{D2D UE } m \text{ as per (13)}, \end{cases} \tag{16}$$

where w_{sm} represents the social distance between SN s and UE m. To calculate the utility of SN $p \in \mathcal{S}$, the social distance of each UE m is incorporated with respect to SN p [43]. The utility of an SN s is the sum of utilities of its associated UEs $m \in \mathcal{L}_s$, for a matching η given by:

$$U_s(\eta) = \sum_{m \in \mathcal{L}_s} U_{sm}(R_{sm}, w_{sm}). \tag{17}$$

Social welfare

Social welfare defines the network wide performance expressed as the sum of the utilities of UEs and SNs [117]:

$$\Gamma(\eta) = \sum_{s \in \mathcal{S}} \sum_{m \in \mathcal{L}_s} U_{sm}(R_{sm}, w_{sm}, \eta), \tag{18}$$

where $\mathcal{S}$ represents the set of SNs in the network. The objective is to maximize the total network wide social welfare given in (18). Unfortunately, maximizing the network-wide social welfare in a centralized manner requires large information exchange between all SCBSs and UEs in the network, calling for a distributed solution with minimum coordination. To address this issue, a clustering mechanism is drive to group mutually-interfering SCBSs into a number of clusters such that SCBSs within a cluster coordinate locally among each other. Specifically, it is assumed that SCBSs are grouped into a set of well-chosen clusters $\mathcal{Z} = \{z_1, z_2, ..., z_{|\mathcal{Z}|}\}$. Let η_z represents the user association (matching), such that $\eta_z(m, p)$ represents the matching of UE m and SN s within cluster $z \in \mathcal{Z}$. Each cluster z consists of locally-coupled SCBSs in terms of mutual interference in which $\mathcal{B}_z$ denotes the number of SCBSs belonging to cluster $z \in \mathcal{Z}$. It is assumed that, in cluster z, SCBSs efficiently offload traffic among each other while satisfying UEs' QoS. Moreover, the matching for each cluster is represented by a vector $\boldsymbol{\eta} = [\eta_1, \eta_2, ..., \eta_{|\mathcal{Z}|}]$. Hereinafter, $\boldsymbol{\eta}$ refer as the *network wide matching*, which captures the utilities of all the UEs and SNs in the network whereas the per cluster matching is denoted by η_z. Finally, the social welfare is defined per cluster z, $\Gamma_z(\eta_z)$ given matching η_z by:

$$\Gamma_z(\eta_z) = \sum_{s \in \mathcal{S}_z} \sum_{m \in \mathcal{M}_z} U_{sm}(R_{sm}, w_{sm}, \eta_z), \tag{19}$$

where $\mathcal{M}_z$ is the set of the UEs, $\mathcal{B}_z$ the set of SCBSs, and $\mathcal{S}_z$ the set of SNs belonging to cluster $z \in \mathcal{Z}$. The objective is to maximize the social welfare for all clusters, which is given by the following optimization problem:

$$\begin{aligned}
\underset{\boldsymbol{\eta}, \mathcal{Z}}{\text{maximize}} \quad & \sum_{\forall z \in \mathcal{Z}} \Gamma_z(\boldsymbol{\eta}) && \text{(20a)} \\
\text{subject to} \quad & |\mathcal{B}_z| \geq 1, \; \forall z \in \mathcal{Z}, && \text{(20b)} \\
& \bigcup_{\forall z \in \mathcal{Z}} \mathcal{B}_z = \mathcal{B}, \; \mathcal{B}_z \cap \mathcal{B}_{z'} = \emptyset, \\
& \forall z, z' \in \mathcal{Z}, \; z \neq z', && \text{(20c)} \\
& \sum_{\forall s \in \mathcal{S}_z} \eta_z(m, s) = 1, \; \forall m \in \mathcal{M}_z, && \text{(20d)}
\end{aligned}$$

where constraints (20b) and (20c) imply that any SCBS is part of one cluster only. The constraint given in (20d) depicts that a given UE m can be matched to only one SN p whereas, SN p can be matched to one or more UEs for a given matching η_z. Solving (20), requires global network information, which can be complex and not practical. Therefore, the subsequent section proposed a distributed solution composed of: 1) dynamic SCBS clustering, 2) flexible user association based on intra-cluster

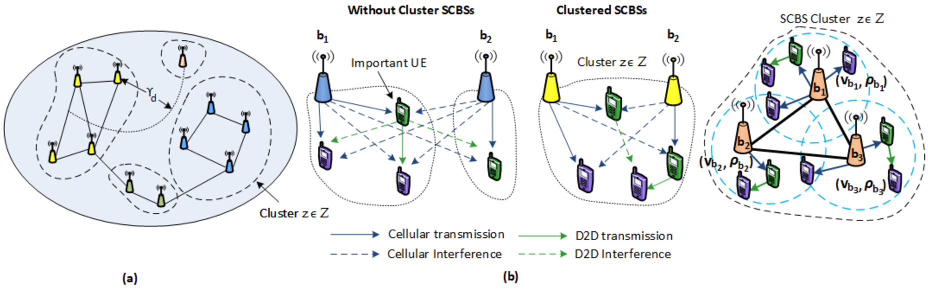

Fig. 9. (a) Clustering among SCBSs, (b) Intra-cell and D2D interference for uncoordinated SCBSs, cluster or cluster-based SCBSs and D2D users interfere with each other within a cluster ([IV]©2017 IEEE).

coordination. The clustering mechanism between SCBSs and intra-cluster coordination are demonstrated in Fig. 9.

3.2.4 Proposed solution

The centralized optimization problem in (20) is difficult to solve and is combinatorial in nature. Developing a decentralized approach based on minimal coordination between neighboring SCBSs is needed. First, a cluster-based mechanism is proposed which incorporates, both location of SCBS and their traffic load. Subsequently, a distributed and self-organized matching algorithm is proposed to dynamically optimize the user association per cluster IV.

In order to calculate the cell load, let us denote η_b as a UE random association[2] to an SCBS b and $0 \leq \phi_b(\eta_b) \leq 1$ as the normalized load of SCBS $b \in \mathcal{B}$, given by:

$$\phi_b(\eta_b) \triangleq \sum_{\forall m \in \mathcal{L}_b \setminus \mathcal{M}_i} \frac{R_{bm}}{R_{bm}^{\max}}, \forall i \in \mathcal{I}, \tag{21}$$

where $R_{bm}^{\max}$ is calculated neglecting the interference from other SCBSs. The average load of each cluster ρ_z for a given matching η_z is the arithmetic average load of its member SCBSs, such that $\rho_z(\eta_z) = \frac{1}{|\mathcal{B}_z|} \sum_{\forall b \in \mathcal{B}_z} \rho_b(\eta_b)$.

[2]Equivalently, the UE can be initially associated to the closest SCBS.

Similarity-based SCBS clustering

Two key factors in clustering SCBS are their physical distance separation and traffic load condition. By utilizing location and traffic load similarities to group SCBSs and employ spectral clustering algorithm [97] to form clusters. The Gaussian affinity matrix $\boldsymbol{Y}$ whose element $y_{b_1 b_2}$ represents joint similarity between two SCBSs $b_1, b_2 \in \mathcal{B}$ based on the distance and load is:

$$\boldsymbol{Y} = \boldsymbol{D}^{\Omega} \cdot \boldsymbol{L}^{1-\Omega}, \tag{22}$$

where, $\boldsymbol{D}$ and $\boldsymbol{L}$ denote the Gaussian distance similarity and Gaussian load dissimilarity matrix, respectively. The parameter $0 \leq \Omega \leq 1$ controls the impact of distance and load similarities on the joint similarity. Let $\boldsymbol{v}_b$ and $\boldsymbol{v}_{b'}$ be the geographical coordinates of SCBS b and b', respectively, in the Euclidean space. The distance similarity $\boldsymbol{D}$ among SCBSs $b, b' \in \mathcal{B}$, $s^d_{bb'}$ given [97]:

$$s^d_{bb'} = \begin{cases} \exp\left(\frac{-||\boldsymbol{v}_b - \boldsymbol{v}_{b'}||^2}{2\sigma_d^2}\right), & \text{if } ||\boldsymbol{v}_b - \boldsymbol{v}_{b'}|| \leq \Upsilon_d, \\ 0, & \text{otherwise,} \end{cases} \tag{23}$$

where the parameter σ_d controls the impact of neighborhood size. For a given Υ_d the range of the Gaussian distance similarity for any two connected SCBSs. Unlike the static distance based clustering in (23), the traffic load of SCBSs varies over time thus, the load based clustering provides a more dynamic manner of grouping neighboring SCBSs. Therefore, clustering SCBSs which have load dissimilarities between SCBS $b, b' \in \mathcal{B}$ is of great interest. Let $s^l_{bb'}$ be an entry of the Gaussian load dissimilarity matrix $\boldsymbol{L}$ between SCBS $b, b' \in \mathcal{B}$ with respect to cell load ρ_b and $\rho_{b'}$, which is given [97]:

$$s^l_{bb'} = \exp\left(\frac{||\phi_b - \phi_{b'}||^2}{2\sigma_l^2}\right), \tag{24}$$

where the parameter σ_l controls the impact of load on the similarity.

Per-cluster social network-aware user association as a matching game with externalities

A social network-aware matching game per cluster $z \in \mathcal{Z}$ is proposed. The proposed game captures both physical and social aspects of the network in which each UE $m \in \mathcal{M}_z$ is associated to the best SN $s \in \mathcal{S}_z$ via a matching $\eta_z : \mathcal{M}_z \longrightarrow \mathcal{S}_z$.

Definition 1 *A matching game is defined by two sets of players ($\mathcal{M}_z$,$\mathcal{S}_z$) and two preference relations $\succ_m$, $\succ_s$ for each UE $m \in \mathcal{M}_z$ to build his preference over SN $p \in \mathcal{S}_z$ and vice-versa in a cluster z. The outcome of the matching game is the association mapping η_z that matches each player $m \in \mathcal{M}$ to player $s = \eta_z(m)$ $p \in \mathcal{S}_z$ and vice versa such that $m = \eta_z(s)$,$m \in \mathcal{M}_z$.*

A *preference relation* $\succ$ is defined as a reflexive, complete and transitive binary relation between players in $\mathcal{M}_z$ and $\mathcal{S}_z$. Thus, a preference relation $\succ_m$ is defined for every UE $m \in \mathcal{M}_z$ over the set of SNs $\mathcal{S}_z$ such that for any two nodes in $s, \tilde{s} \in \mathcal{S}_z^2, s \neq \tilde{s}$ and two matchings $\eta_z, \eta_z' \in \mathcal{M}_z \times \mathcal{S}_z, \eta_z \neq \eta_z'$,$s = \eta_z(m)$,$\tilde{s} = \eta_z'(m)$:

$$\begin{aligned}&(s, \eta_z, \boldsymbol{\eta}_{-z}) \succ_m (\tilde{s}, \eta_z', \boldsymbol{\eta}_{-z}) \Leftrightarrow \\ &U_{sm}(R_{sm}, w_{sm}, \eta_z, \boldsymbol{\eta}_{-z}) > U_{\tilde{s}m}(R_{\tilde{s}m}, w_{\tilde{s}m}, \eta_z', \boldsymbol{\eta}_{-z}),\end{aligned} \tag{25}$$

where $(s,m) \in \eta_z$ and $(\tilde{s},m) \in \eta_z'$. Similarly the preference relation $\succ_s$ for SN s over the set of UEs $\mathcal{M}_z$ is defined such that for any two UEs $m, \tilde{m} \in \mathcal{M}_z, m \neq \tilde{m}$,$m = \eta_z(s)$, $\tilde{m} = \eta_z'(s)$:

$$(m, \eta_z, \boldsymbol{\eta}_{-z}) \succ_s (\tilde{m}, \eta_z', \boldsymbol{\eta}_{-z}) \Leftrightarrow U_s(\eta_z) > U_{\tilde{s}}(\eta_z'). \tag{26}$$

Each SN and UE independently rank one another based on the respective utilities in (16) and (17) that capture the interference and social ties among nearby UEs. In particular, the considered game is a matching game with *externalities* due to mutual interference and social ties between nodes, which differs from classical applications of matching theory in wireless such as those in [118, 119, 120]. The objective of each player is to maximize its own utility, by associating to its most preferred SN.

3.2.5 Main results

In simulations, it is assumed that UEs and SCBSs are uniformly distributed over the area of $500 \times 500\,\mathrm{m}^2$. Only one UE is selected as important UE per SCN. There is no power control, and thus the power is uniformly divided among UEs. A cluster radius of 200 m with inter-site distance of 40 m is assumed. The transmission radius of 50 m and 20 m is considered for SCBS and D2D communication, respectively. A common full-buffer traffic model is considered for UEs in our simulations. The performance of the social-aware approach is compared with the baseline classical association approaches. The first baseline approach assumes maximum reference signal received power (max-RSRP) for cell association. The second baseline approach assumes

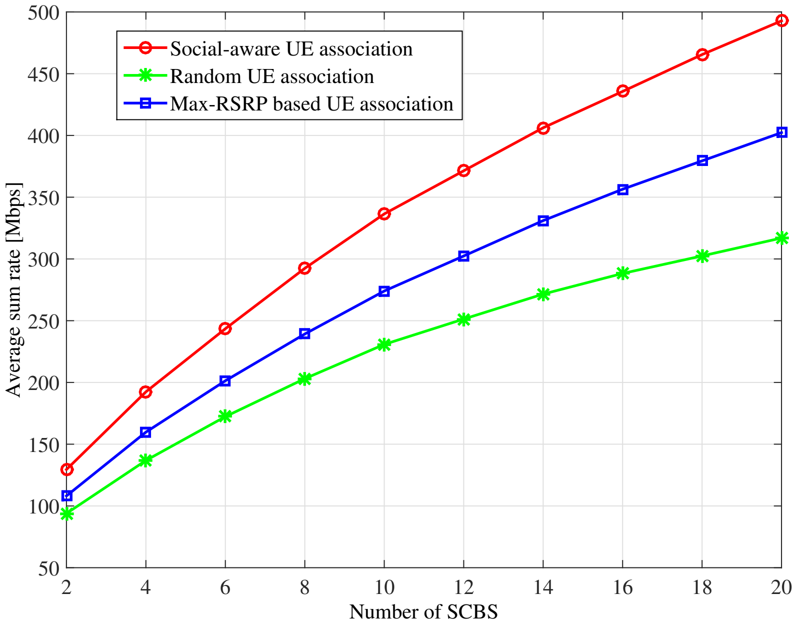

Fig. 10. Average sum rate for a fixed number of UEs (M=10) per SCBS, for the proposed and baseline approaches ([IV]©2017 IEEE).

random cell association. In the random association, important UEs are chosen randomly and UEs are randomly associated to SN within their D2D coverage radius. For the proposed social-aware UE-association with clustering approach a dynamic clustering method is used, in which the number of clusters dynamically changes. Moreover, all statistical results are averaged over a large number of independent runs and high dense network deployment.

Fig. 10 shows the average sum rate as a function of the density of SCBSs N, and fixed number of UEs per SCBS $M = 10$. Fig. 10 clearly shows that, in the proposed social-aware approach, user association improves the sum rate. In particular, the results show that, as the number of SCBSs increases, the average sum rate increases. This is due to the fact that, an increase in the number of SCBSs increases the number of important UEs, hence UEs associate with an important UE or SCBS based on their respective utility. Fig. 10, also shows that the performance improvement in terms of sum rate for the proposed social-aware approach increases with the increase in number of SCBSs. It is further observed that the proposed social-aware approach yields significant

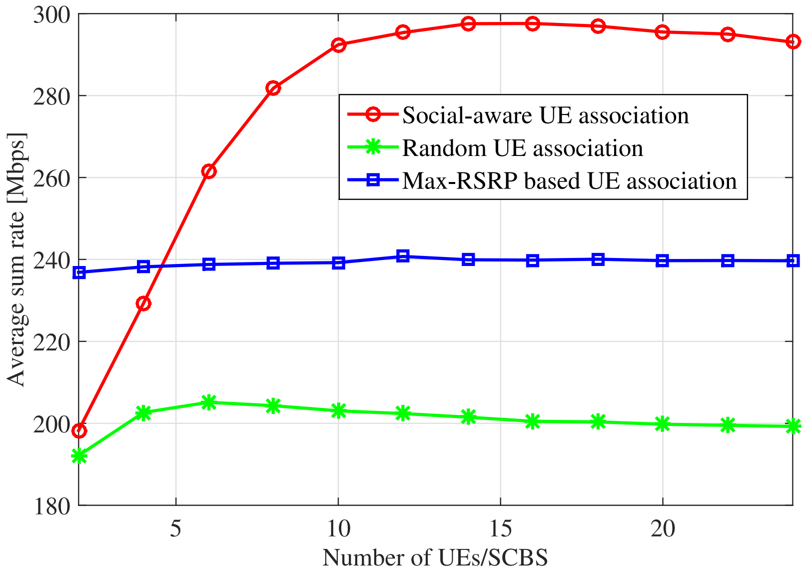

Fig. 11. Average sum rate for a fixed number of SCBS (B=8), under the considered approaches ([IV]©2017 IEEE).

performance gains for all network size, reaching up to 23% over the max-RSRP based approach and 56% over the random UE association approach.

Fig. 11 shows the average sum rate for a fixed number of SCBSs $B = 8$ and varying density of UEs. It is worth mentioning that the proposed approach is suited for dense networks where large number of UEs per SCBS are deployed. It can be seen from the figure that, there is notable performance gain in terms of average sum rate for the proposed approach as compared to random and max-RSRP approach for a varying number of UEs from 6 to 24 per cell. Moreover, it is also noted that in random UE association, UEs are associated to any SN within vicinity without consideration of RSRP and social-ties between UEs. From Fig. 11, it can also be observed that, by increasing the number of UEs, the average sum rate increases up to 48% and 24% compared to random UE association and max-RSRP, respectively. Furthermore, the results show that having fewer UEs per SCBS such as 2 and 4 UEs/SCBS the max-RSRP association approach outperforms the proposed approach. This is due to the under utilization of the second time-slot τ_1 if no D2D links are formed in neighboring SCBSs.

4 Resource allocation in V2V network

As indicated in Section 2.2.2, a proper RRM framework is required for V2V communication to satisfy latency and reliability. Typically, when communicating vehicles are within network coverage, the RSU can centrally coordinate transmissions without resource reuse, thus minimizing resource utilization. To enhance resource utilization time-frequency resources must be shared among vehicles such that interference is mitigated. RRM is a key for the vehicular application to reduce interference and satisfy URLLC requirements. This chapter proposes a series of solutions based on cellular D2D/V2V links for supporting safety-related V2V communications, with a focus on RRM. First, Section 4.1 introduces a QoS-aware, distributed self-organizing resource allocation mechanism for V2V. Next Section 4.2 proposes latency- and reliability-aware resource allocation approaches for V2V communications.

4.1 QoS-aware V2V communication (Paper [II])

In paper [II], a distributed self-organizing resource allocation mechanism for V2V communication is proposed. The proposed approach ensures continuous (or periodic) transmission opportunities for vehicular applications such as autonomous safety services in the V2V underlay, while reducing control overhead and interference to other vehicles. Due to the localized nature of traffic safety applications, a new dynamic cluster formation approach is proposed that allows vehicles to dynamically optimize their resource allocation, depending on the current channel quality information (CQI), reliability requirements and network topology. In such V2V networks, performing dynamic approaches requires a knowledge of the entire network which incurs significant overhead. Therefore, the proposed schemes allow grouping vehicle pairs into dynamic clusters within which each such pair can coordinate their transmission. Moreover, a intra-cluster coordination mechanism is proposed which allocates resources to each vehicle pair while minimizing a cost function which captures successful transmissions and traffic load. To this end, the problem is cast as many-to-one matching game per cluster with externalities in which the RBs and VUEs are the players, which rank one another based on a set of preferences seeking suitable and stable allocation. A distributed algorithm is proposed to solve the matching game that allows RBs and VUEs to self-organize and to maximize their utilities within their respective clusters. In addition, the proposed

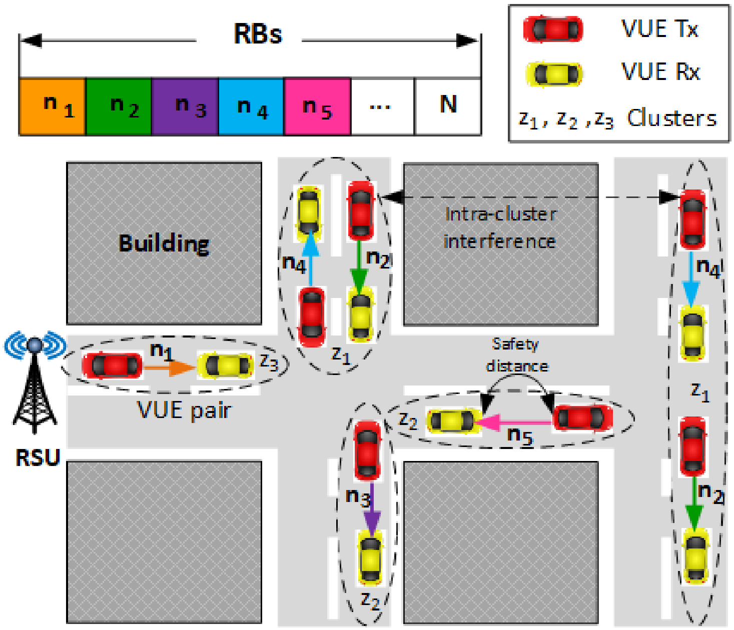

Fig. 12. V2V communications scenario for a Manhattan grid model with cluster formation $Z = \{z_1, z_2, z_3\}$. If two V-UE pairs in close proximity use the same RB, interference can be very high ([II]©2016 IEEE).

algorithm is shown to converge to a stable matching in which no player has an incentive to match to another player, even in the presence of externalities. Simulation results validate the effectiveness of the proposed approach and show significant performance gains compared to the baseline state-of-the-art approach.

4.1.1 System model

A Manhattan grid layout is considered for simulations, such that K number of VUE pairs (counted in terms of transmitters) share resources. Let $\mathcal{K} = \{1, \dots K\}$ and $\mathcal{N} = \{1, \dots N\}$ be the set of VUE pairs and the set of orthogonal resource blocks (RBs). It is assumed that all VUEs are under the coverage of a single RSU. Each VUE pair $k \in \mathcal{K}$ uses one RB whereas one RB may be shared among multiple VUEs and cause interference. The considered scenario is illustrated in Fig. 12. It is further assumed that each VUE pair has a QoS requirement based on its individual packet size $1/\mu_k(t)$ and packet arrival rate $\lambda_k(t)$. In this respect, the traffic influx rate $\phi_k(t) = \lambda_k(t)/\mu_k(t)$ and data rate $R_{kn}(t)$ of k VUE pair over RB $n \in \mathcal{N}$ at time slot t. The *time load* over RB n is the fractional time in slot t required to deliver the requested traffic for VUE k which is defined as:

$$\rho_{kn}(t) := \frac{\phi_k(t)}{R_{kn}(t)}. \tag{27}$$

Since fast moving vehicles induce shorter channel coherence times, frequent gathering CQI is not feasible thus, a CQI that periodically varies over a time period T is considered at the RSU level. Therefore, the expected time load estimation $\bar{\rho}_k$ for VUE k is:

$$\rho_k(t) = \frac{1}{|\mathcal{N}|}\sum_{n=1}^{N} \rho_{kn}(t), \tag{28}$$

$$\bar{\rho}_k \triangleq \frac{1}{T}\sum_{t=1}^{T} \rho_k(t). \tag{29}$$

The achievable data rate for VUE pair $k \in \mathcal{K}$ over RB n at location $\boldsymbol{x}$ is written as:

$$R_{kn}(t) = \omega \log_2\big(1+\gamma_{n,k}(t)\big), \tag{30}$$

where ω is the bandwidth of RB $n \in \mathcal{N}$. The achievable SINR $\gamma_{kn}(t)$ at V-UE pair $k \in \mathcal{K}$ over RB n at location $\boldsymbol{x}$ at time t is:

$$\gamma_{kn}(t) = \frac{P_{kn}h_{kn}(t)}{\sum_{k' \in \mathcal{K}\setminus k} P_{k'n}h_{k'n}(t) + N_0}, \tag{31}$$

where P_{kn} is the transmission power and $h_{kn}(t)$ is the channel gain of VUE pair k over RB n, while N_0 is the noise spectral density. The interference term in the denominator represents the aggregate interference at VUE k caused by the transmissions of other VUEs $k' \in \mathcal{K} \setminus \{k\}$ on same RB. Here, for tractability, we assume that RB n allows VUE k to transmit if the experienced $\gamma_{kn}(t)$ exceeds a target SINR threshold $\overline{\gamma}_{n,k}(t)$. Otherwise, V-UE k cannot transmit on RB n, such that $\overline{\gamma}_{n,k}(t)$ is equal for each V-UE pair. Due to the fact that vehicles are continuously changing their location and generating different traffic load over time, it is not practical to perform resource allocation at each time instance.

4.1.2 Problem formulation

Using a central controller to allocate resources for every V2V pair is impractical due to fast-varying CQI and stringent reliability constraints. Our objective is to propose an efficient and self-organizing resource allocation approach while eliminating the frequent collection of CQI information. In this section, the problem of VUEs cluster formation and flexible resource allocation is studied. The proposed approach incorporates vehicles' geographical information and traffic patterns. Then, the framework of matching theory [98] is utilized to develop a distributed and self-organizing solution. Whenever an RB is allocated to a VUE pair, it should maintain QoS requirement via a resource allocation process. For proper resource allocation VUE pairs need to coordinate with the rest of the network through a central controller and thus, it incurs large information exchange among vehicles. Therefore, a number of VUE pairs are grouped into sets of clusters based on mutual interference and traffic load. In view of the above, lets assume $\mathcal{Z}$ be the set of clusters. Each cluster $z \in \mathcal{Z}$ is of dynamic size and changes over time according to proximity-based information and traffic load. Let, η_z be the per-cluster resource allocation variable which represents the mapping (matching) of VUE pair k and RB n within cluster z. Each cluster z consists of temporally and spatially coupled VUEs due to mutual interference. Let S_z be the total number of VUE pairs satisfying the target SINR inside cluster $z \in \mathcal{Z}$. Here, let $\mathcal{K}_z$ denotes the set of VUEs belonging to cluster z and $\mathcal{N}_z$ denotes the set of orthogonal resource blocks assigned to cluster z. In each cluster z, VUEs efficiently reuse resources while simultaneously satisfying their QoS. Moreover, the allocation vectors for each cluster are collected in a vector $\boldsymbol{\eta} = [\eta_{z_1}, \dots \eta_{|\mathcal{Z}|}]$. Hereinafter, $\boldsymbol{\eta}$ referred as the "network wide matching" of all clusters. The total expected time load of each cluster is calculated as the aggregated load of each cluster's member $\bar{\rho}_z(\eta_z) = \sum_{k \in \mathcal{K}_z} \bar{\rho}_k$. The per-cluster cost $\Gamma_z(\eta_z)$ for a given mapping η_z is defined as:

$$\Gamma_z(\eta_z) = \frac{[\bar{\rho}_z(\eta_z)]^{\alpha}}{[\frac{S_z}{K_z}]^{\beta}}, \tag{32}$$

where the coefficients α and $\beta > \alpha$ are weight parameters that indicate the impact of the load and number of satisfied VUE pairs. Our objective is to minimize the network cost, which is given by the following optimization problem:

$$\begin{aligned}
\underset{\{\boldsymbol{\eta}, \mathcal{Z}\}}{\text{minimize}} \quad & \sum_{z \in \mathcal{Z}} \Gamma_z(\eta_z), && \text{(33a)}\\
\text{subject to} \quad & |\mathcal{K}_z| \geq 1, \ \forall z \in \mathcal{Z}, && \text{(33b)}\\
& \mathcal{K}_z \cap \mathcal{K}_{z'} = \emptyset, \ \forall z, z' \in \mathcal{Z}, \ z \neq z', && \text{(33c)}\\
& \sum_{n=1}^{N} \eta_z(k,n) \leq 1, \ \forall k \in \mathcal{K}_z, && \text{(33d)}\\
& \bigcup_{\forall k \in \mathcal{K}_z} \eta_z(k,n) \leq |\mathcal{N}_z|, \ \forall z, \forall n. && \text{(33e)}
\end{aligned}$$

Here, constraints (33b) and (33c) ensure that any VUE is part of one cluster only. (33d) captures the fact that a given VUE pair k can be matched to only one RB n while an, RB n can be matched to one or more VUEs for a given matching η_z. Constraint (33e) states that VUE pairs can reuse the resources within set $\mathcal{N}_z$.

4.1.3 Proposed approach

The centralized optimization problem in (33) is challenging to solve as it is combinatorial in nature. To that end, a decentralized self-organizing approach based on minimal coordination between neighboring VUEs is proposed. Specifically, first, a dynamic cluster formation mechanism is devised which incorporates, both geographical proximity of VUEs and their traffic nature (e.g., traffic load, interference). Next, an intra-cluster resource allocation approach is proposed, in which VUEs inside a cluster and RSU-controlled RBs interact and make resource allocation decisions based on load-aware utilities. The problem is formulated as a matching game with externalities in which the VUEs and RBs build preferences over one another so as to choose their own utilities [II].

4.1.4 Main results

For simulations, a single cell Manhattan model is considered. VUEs moves at a fixed speed of 50 km/h along the defined roads. The line-of-sight (LOS) and non-line-of-sight (NLOS) path loss model for V2V communication is computed using the Berg recursive model [121]. To compare the proposed approach with the reference approach proposed in [73]. Particularly, for the reference approach, the total area is divided into fixed equal size clusters such that a fixed number of RBs are allocated to each cluster while clusters having more load in terms of traffic gets more RBs. It is worth mentioning that the clusters are static over variant load which in fact make the proposed dynamic approach better in performance.

Fig. 13, shows the percentage of VUEs which achieved the desired target SINR for different numbers of VUEs and RBs. From this figure, it is observed that the proposed approach significantly reduces the number of outages compared to the reference scheme for all network sizes. The centralized problem in Fig. 13 shows that, almost 100% VUEs pairs satisfying the target SINR in the case of 10 and 15 VUE pairs when $N = 15$ RBs. The advantage of the proposed approach reaches up to 49% and 50% of gain

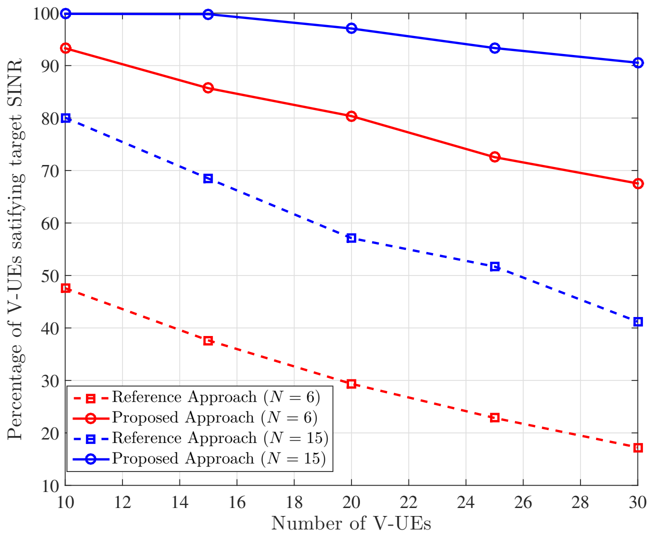

Fig. 13. Percentage of VUEs satisfying the target SINR for different densities of VUEs and different number of RBs under the considered approaches ([II]©2016 IEEE).

when compared to the baseline approach with $K = 30$ VUEs for $N = 6$ and $N = 15$ RBs, respectively.

4.2 Dynamic latency- reliability-aware resource allocation in V2V communication (Papers [V, VI])

Papers [V, VI], focus on URLLC aspects of V2V communication. Supporting URLLC is key for vehicular traffic safety and other mission-critical applications. A novel proximity and QoS-aware resource allocation framework for V2V communication is proposed. The objective is to find an efficient RB allocation and power optimization (RAPO) solution while meeting the latency and reliability requirements. The proposed scheme incorporates the physical proximity and traffic demands of vehicles to minimize the total transmission power over the allocated RBs under reliability and queuing latency constraints. A Lyapunov framework is used to decompose the power minimization problem into two interrelated sub-problems: RB allocation and power optimization. To minimize the overhead introduced by frequent information exchange between vehicles and the RSU, the resource allocation problem is solved in a semi-distributed fashion.

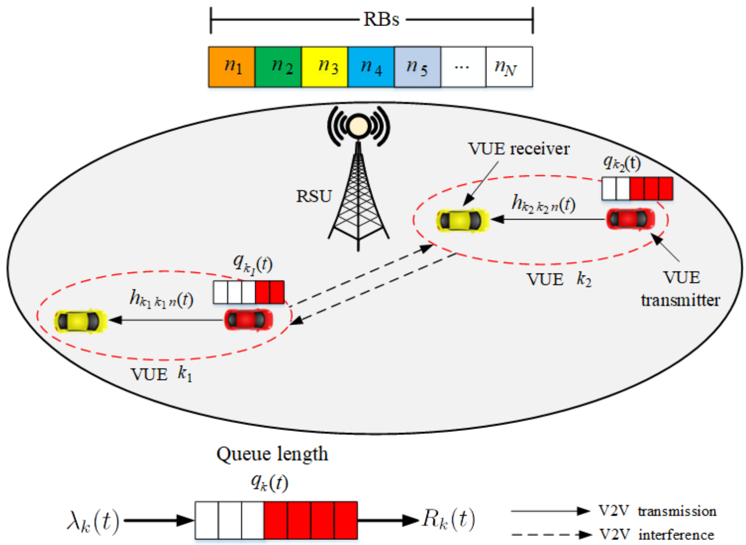

Fig. 14. Interference between different VUE pairs k_1 and k_2 using the same set of RBs $n \in \mathcal{N}$ ([VI]©2018 IEEE).

First, a novel RSU-assisted virtual clustering mechanism is proposed to group vehicles into disjoint clusters based on mutual interference. Second, a per-cluster matching game is proposed to allocate RBs to each vehicle user equipment (VUE) based on vehicles' traffic demands and their latency and reliability requirements. In the formulated one-to-many matching game, VUE pairs and RBs rank one another using preference relations that capture both the queue dynamics and interference. To solve this game, a semi-decentralized algorithm is proposed which enables the VUEs and RBs to reach a stable matching. Finally, a latency- and reliability-aware power allocation solution is proposed for each VUE pair over the assigned subset of RBs. Simulation results for a Manhattan model show that the proposed scheme outperforms a state-of-the-art baseline.

4.2.1 System model

A V2V network following the Manhattan mobility model is assumed. The V2V network is composed of a single RSU covering set $\mathcal{K}$ of K VUE transmitter-receiver (Tx-Rx) pairs. During the entire communication period, it is assumed that the VUE pair configuration is fixed. In this work, the available resources are represented in both frequency and time domains, where the whole bandwidth is divided into a set of $\mathcal{N}$ RBs as shown in Fig. 14.

Additionally, $|h_{kk'n}(t)|^2$ denotes the channel gain of a VUE transmitter of pair k to the VUE receiver of pair k' over RB n in time slot t. Let $x_{kn}(t)$ be defined as the indicator variable indicating that VUE k uses RB n at time slot t. To transmit information to its VUE receiver, the transmitter of pair k allocates power $p_{kn}(t)$ over RB n in time slot t with $\sum_{n\in\mathcal{N}} x_{kn}(t)p_{kn}(t) \leq P_k^{\max}$ where $P_k^{\max}$ is VUE pair k's total power budget. Thus, the data rate of VUE pair k in time slot t is:

$$R_{kn}(t) = \omega \log_2\left(1 + \frac{x_{kn}(t)p_{kn}(t)|h_{kkn}(t)|^2}{N_0 + I_{kn}(t)}\right), \tag{34}$$

$$R_k(t) = \sum_{n\in\mathcal{N}} R_{kn}(t), \tag{35}$$

where ω represents the bandwidth of an RB and N_0 is the noise spectral density. The interference term $I_{kn}(t)$ in (34) represents the aggregate interference at VUE k caused by the transmission of other VUEs $k' \in \mathcal{K}$ on the same RB n, and is given by:

$$I_{kn}(t) = \sum_{k'\in\mathcal{K}\setminus k} x_{kn}(t)p_{k'n}(t)|h_{k'kn}(t)|^2. \tag{36}$$

Moreover, each VUE transmitter has a queue buffer to store data for its VUE receiver. Let $\boldsymbol{q}(t) = [q_1(t),\ldots,q_K(t)]$ be the traffic queue length vector in time slot t where $q_k(t)$ denotes the queue length of a given VUE pair $k \in \mathcal{K}$. The evolution of $q_k(t)$ is given by:

$$q_k(t+1) = \left[q_k(t) - \tau R_k(t)\right]^+ + \lambda_k(t), \tag{37}$$

where, τ is the time slot duration while $\lambda_k(t)$, with $\bar{\lambda}_k = \mathbb{E}[\lambda_k(t)]$, is the traffic arrival at the transmitter of pair k in time slot t. Here $[\cdot]^+ = \max\{\cdot, 0\}$ indicates that the amount of served data cannot exceed the amount of the stored data in the queue. Without loss of generality, lets assume $q_k(1) = 0, \forall k \in \mathcal{K}$, as the initial queue length.

4.2.2 Problem formulation

In order to increase the reliability and reduce latency, a large number of data packets needs to be sent within the given latency bound. However, this might over-allocate resources (i.e., RB, transmit power) to a given VUE. Typically, the transmit power in successive slots is coupled with the resource allocation and queue dynamics (i.e., queue length). Therefore, the transmission power can better capture the real-world performance of a vehicular network while minimizing the queuing latency and improving reliability. The RSU's objective is to find an optimal RB allocation and power allocation policy which minimizes the network transmission power while satisfying queuing latency and reliability. Let $\boldsymbol{X}(t) = [x_{kn}(t)]$ be the RB allocation matrix and $\boldsymbol{P}(t) = [p_{kn}(t)]$ be the power matrix in time slot t. Therefore, a joint RAPO problem is posed as follows whose goal is to minimize time-average power:

$$\underset{X(t),P(t)}{\text{minimize}} \quad \sum_{k\in\mathcal{K}}\sum_{n\in\mathcal{N}} \bar{p}_{kn} \tag{38a}$$

$$\text{subject to} \quad \lim_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} \mathbb{E}[q_k(t)] \le \bar{\lambda}_k d_k,\ \forall k \in \mathcal{K}, \tag{38b}$$

$$\lim_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} \mathbb{E}\big[\mathbb{1}\{q_k(t) \ge L_k\}\big] \le \varepsilon_k,\ \forall k \in \mathcal{K}, \tag{38c}$$

$$\sum_{n\in\mathcal{N}} x_{kn}(t) \le N_k,\ \forall k \in \mathcal{K}, \tag{38d}$$

$$\sum_{n\in\mathcal{N}} x_{kn}(t) p_{kn}(t) \le P_k^{\max},\ \forall t, k \in \mathcal{K}, \tag{38e}$$

$$p_{kn}(t) \ge 0,\ \forall t, k \in \mathcal{K}, n \in \mathcal{N}, \tag{38f}$$

$$x_{kn}(t) \in \{0,1\},\ \forall t, k \in \mathcal{K}, n \in \mathcal{N}, \tag{38g}$$

where $\bar{p}_{kn} = \lim_{T\to\infty} \frac{1}{T}\sum_{t=1}^{T} p_{kn}(t)$ is the time-averaged power consumption of VUE pair k over RB n. Constraint (38b) is VUE k's queuing latency requirement while (38c) captures the reliability constraint of VUE k. In addition, (38d) indicates that each VUE k can be assigned up to N_k RBs. Constraint, (38e) ensures that total transmit power of VUE k over the allocated RBs is within the maximum power budget.

4.2.3 Proposed solution

Problem decomposition using Lypunov optimization

Although the optimal $\boldsymbol{X}(t)$ and $\boldsymbol{P}(t)$ can be obtained by dynamic programming, such an approach is computationally complex and requires the statistics of traffic arrivals and CSI. To alleviate computational complexity, the tools from Lyapunov stochastic optimization [122, 123, 124] are invoked which require a partial knowledge of the CSI and provide a tractable solution compared to dynamic programming.

Using Lyapunov optimization [122], the time-average inequality constraints (38b) and (38c) can be satisfied by converting them into *virtual queues* and maintaining their stability. Therefore, lets define the following virtual queue vectors $\boldsymbol{j}(t) = [j_1(t), \ldots j_K(t)]$ and $\boldsymbol{f}(t) = [f_1(t), \ldots f_K(t)]$ corresponding to the constraints (38b) and (38c), respectively. Accordingly, the virtual queues are updated as follows:

$$j_k(t+1) = \left[j_k(t) + q_k(t+1) - \bar{\lambda}_k d_k\right]^+, \tag{39}$$

$$f_k(t+1) = \left[f_k(t) + \mathbb{1}\{q_k(t+1) \geq L_k\} - \varepsilon_k\right]^+. \tag{40}$$

The constraints (38b) and (38c) are satisfied if the corresponding virtual queues are *mean rate stable* [122], i.e., $\frac{1}{T}\lim_{t\to\infty}\mathbb{E}[|j_k(t)|] = 0$ and $\frac{1}{T}\lim_{t\to\infty}\mathbb{E}[|f_k(t)|] = 0, \forall k \in \mathcal{K}$. Hereafter, the problem in (38) is equivalent to minimizing the network-wide average transmit power subject to mean-rate stability for virtual queues. Subsequently, the solution to (38) can be found by minimizing the upper bound at each slot t [122], which is given by:

$$\begin{aligned} &\underset{\boldsymbol{X}(t),\boldsymbol{P}(t)}{\text{minimize}} \quad \sum_{k\in\mathcal{K}}\sum_{n\in\mathcal{N}} v p_{kn}(t) - \tau\Big(j_k(t) + f_k(t) + 2q_k(t) + 2\lambda_k(t)\Big)R_{kn}(t), \\ &\text{subject to} \;\; \text{(38d)–(38g)}, \end{aligned} \tag{41}$$

The parameter v is a non-negative constant that captures a trade-off between the optimal solution and network-wide queue stability.

Semi-distributed resource allocation

From (41), it can be observed that RB allocation is coupled with the power allocation problem. The formulation is an NP-hard mixed-integer programming problem which is challenging to solve [125]. Moreover, to centrally find the optimal $\boldsymbol{X}(t)$ and $\boldsymbol{P}(t)$ in each time slot, the RSU requires full global information, i.e., CSI and QSI of the network. This is impractical for vehicular communication as the frequent exchange of local information (considering high refresh rates) between RSU and VUE pairs incurs high overhead. Consequently, let $\mathcal{Z}$ be the set of Z clusters. Each cluster $z \in \mathcal{Z}$ is of dynamic size and changes across different time frames according to the geographical proximity and traffic patterns of VUEs. let $\mathcal{K}_z(i)$ be set of VUEs belonging to cluster z at time frame i. Note that $\mathcal{K}_z(i), \forall z \in \mathcal{Z}$, are static during one time frame but dynamic over frames. In each cluster z, each VUE $k \in \mathcal{K}_z$ efficiently uses the allocated RBs while optimizing its power and satisfying (38b) and (38c). Furthermore, one RB cannot be shared by two VUE pairs at the same time within the same cluster. This restriction is imposed to avoid high interference created by the neighboring VUEs. Hence, to mitigate interference and minimize overhead caused by signaling VUEs are clustered into groups based on similar attributes. In this regards, geographical information and traffic arrival similarities to group VUEs into distinct clusters as demonstrated in Fig. 15. Following

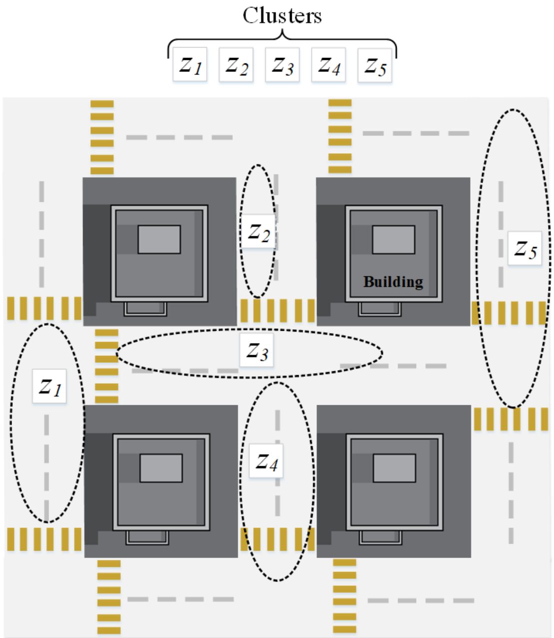

Fig. 15. RSU-assisted cluster formation among VUE pairs ([VI]©2018 IEEE).

the idea of cluster formation and resource allocation, the network-wide objective can be written as:

$$\underset{\mathcal{Z}(i),\boldsymbol{X}(t),\boldsymbol{P}(t)}{\text{minimize}} \sum_{z\in\mathcal{Z}} \sum_{n\in\mathcal{N}_z} \Gamma_{zn}(t) \tag{42a}$$

$$\text{subject to} \quad \sum_{k\in\mathcal{K}_z} x_{kn}(t) \leq 1, \; \forall z \in \mathcal{Z}, n \in \mathcal{N}, \tag{42b}$$

$$\sum_{n\in\mathcal{N}} x_{kn}(t) \leq N_k, \; \forall k \in \mathcal{K}_z, z \in \mathcal{Z}, \tag{42c}$$

$$x_{kn}(t) \in \{0,1\}, \; \forall n \in \mathcal{N}, k \in \mathcal{K}_z, z \in \mathcal{Z}, \tag{42d}$$

$$\sum_{n\in\mathcal{N}} p_{kn}(t) \leq P_k^{\max}, \; \forall k \in \mathcal{K}_z, z \in \mathcal{Z}, \tag{42e}$$

$$p_{kn}(t) \geq 0, \; \forall n \in \mathcal{N}, k \in \mathcal{K}_z, z \in \mathcal{Z}, \tag{42f}$$

$$|\mathcal{K}_z(i)| \geq 1, \; \forall z \in \mathcal{Z}, \tag{42g}$$

$$\mathcal{K}_z(i) \cap \mathcal{K}_{z'}(i) = \emptyset, \; \forall z, z' \in \mathcal{Z}, \; z \neq z', \tag{42h}$$

$$\bigcup_{z\in\mathcal{Z}} \mathcal{K}_z(i) = \mathcal{K}. \tag{42i}$$

Here, $\Gamma_{zn}(t) = \sum_{\forall k \in \mathcal{K}_z} \Gamma_{kn}(t)$ is the aggregated objective function of the VUEs in cluster z. Furthermore, constraint (42b) captures the fact that a given RB n can be assigned to only one VUE $k \in \mathcal{K}_z$ inside a cluster while, a VUE k can be associated to one or more RBs. Constraint (42c) states that each VUE k can be assigned up to N_k RBs. Constraints (42e)–(42h) imply that each VUE pair belongs to one cluster whereas each cluster has at least one VUE pair.

In this regard, by utilizing the geographical information and traffic arrival similarities, VUEs are grouped into distinct clusters. Therefore, a dynamic clustering strategy is introduced, which takes into account both the physical proximity of VUEs and their traffic patterns (e.g., traffic arrival, interference). However, solving (42) requires knowledge of all clusters i.e., $\boldsymbol{X}(t), \boldsymbol{P}(t)$, and inter- and intra-cluster interference in the network, which can be impractical. Therefore, we decouple the RB allocation problem from the power allocation problem. One of the key objectives of the proposed approach is to minimize overhead and interference between neighboring VUEs. Hence, to mitigate interference and minimize overhead caused by signaling, VUEs are first grouped into distinct clusters based on geographical information and traffic arrival similarities [VI]. A low complexity matching algorithm is proposed to match RBs to the VUEs inside each cluster. Given the outcome of the matching, a power allocation problem is formulated to optimally allocate power to VUEs over the matched RBs.

VUE-RB matching

To overcome the combinatorial nature of the RB allocation problem (42b)–(42d), the framework of matching theory [126, 98, 127, 128] is used. A matching game per-cluster $X_z : \mathcal{K}_z \longrightarrow \mathcal{N}$ is essentially a two-sided assignment problem between two disjoint sets of players, e.g., the set of VUEs $\mathcal{K}_z$ and the set of RBs $\mathcal{N}$, in which the players of one set tries to match (associate) to the most suitable players of the other set according to their own *preference relations*. Further, for a *one-to-many* matching game, each player in $\mathcal{K}_z$ is matched to one or multiple players in $\mathcal{N}$ whereas each player in $\mathcal{N}$ is matched to at most one player in $\mathcal{K}_z$. An example of matching between VUEs and RBs inside cluster z demonstrated in Fig. 16. The preferences of the sets of VUEs and RBs $(\mathcal{K}_z, \mathcal{N})$ denoted by $\succ_k$ and $\succ_n$, respectively, represents ranking of players from one set over the other set. Finally, in order to find a stable solution for the proposed matching game, the DA algorithm is adopted [90]. Moreover, the proposed algorithm is guaranteed to

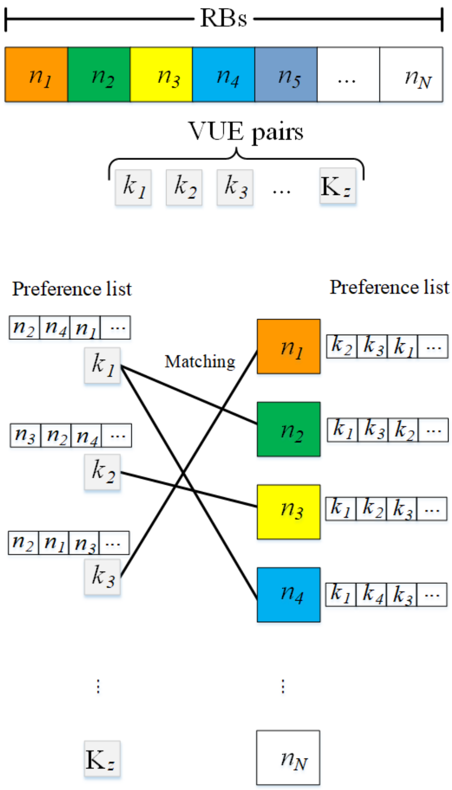

Fig. 16. Per-cluster VUE-RB matching in which VUE and RB preferences are based on their utility ([VI]©2018 IEEE).

converge to a two-sided stable matching X_z between VUEs and RBs. To this end, next a latency and reliability-aware power allocation solution is proposed.

4.2.4 Latency- and reliability-aware power allocation at the VUE

Once the subset of RBs $\mathcal{N}_k$ is allocated to the VUEs inside cluster z, each VUE $k \in \mathcal{K}_z$ inside its respective cluster z optimizes the transmit power over the allocated RBs, i.e., $\mathcal{N}_k$. The optimal power allocation is performed locally by each VUE pair over allocated RBs ensuring latency and reliability constraints as per (38c) and (38d), respectively. The inter-cluster interference and power allocation for VUEs within in each zone is shown in Fig. 17. Thus, given the RBs allocated by the matching algorithm, the local power

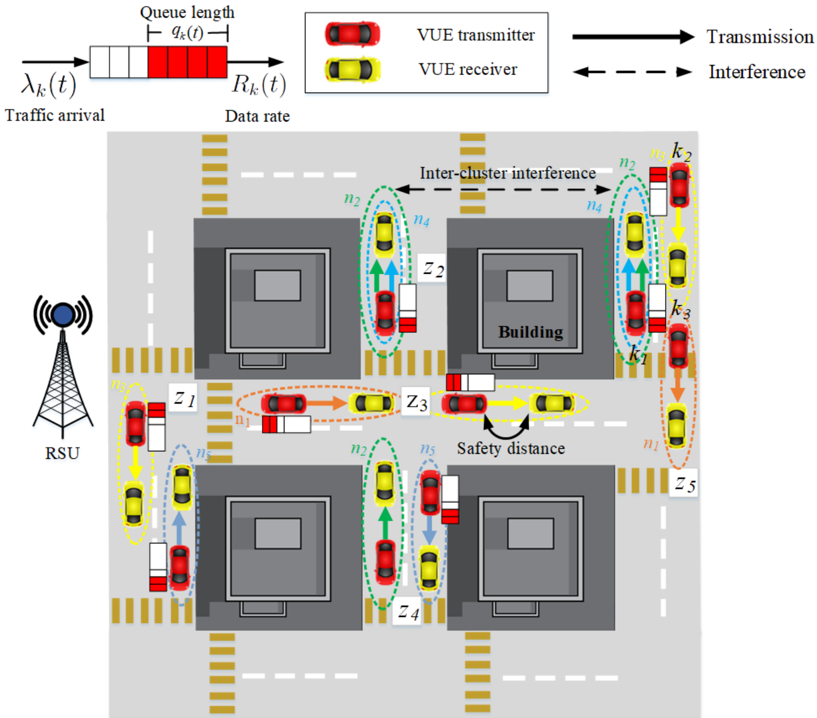

Fig. 17. Inter-cluster interference and power allocation for V2V transmissions ([VI]©2018 IEEE).

allocation can be written as a convex optimization problem:

$$\begin{aligned} \underset{p_{kn}}{\text{minimize}} \quad & \sum_{n\in\mathcal{N}_k} v p_{kn} - \sum_{n\in\mathcal{N}_k} \tau\omega\big(j_k + f_k + 2q_k + 2\lambda_k\big) \\ & \times \mathbb{E}_{I_{kn}^{\text{inter-cluster}}}\left[\log_2\left(1+\frac{p_{kn}|h_{kkn}|^2}{\sigma^2+I_{kn}^{\text{inter-cluster}}}\right)\right] && \text{(43a)} \\ \text{subject to} \quad & \sum_{n\in\mathcal{N}_k} p_{kn} \le P_k^{\max},\ \forall k\in\mathcal{K}_z, && \text{(43b)} \\ & p_{kn} \ge 0,\ \forall n\in\mathcal{N}_k, && \text{(43c)} \end{aligned}$$

which is solved at each time instant although we omit the time index t for notational simplicity.

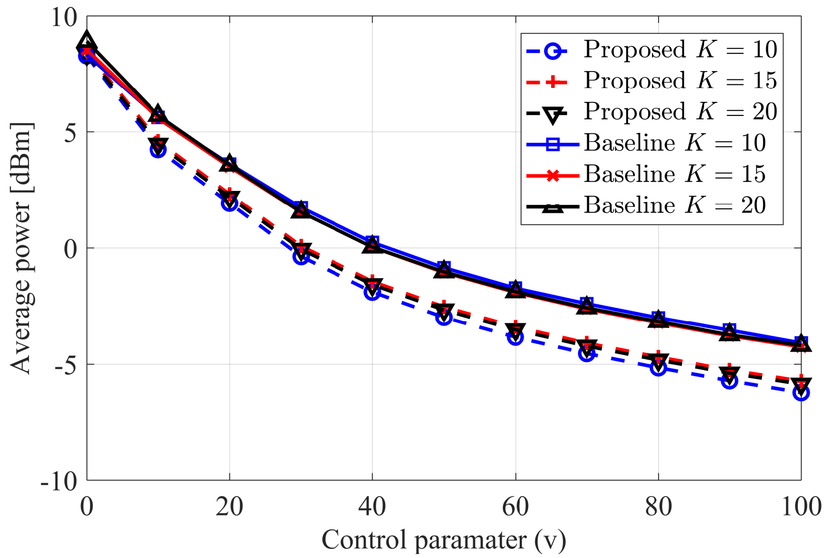

Fig. 18. Trade-off between average power and control parameter v for various densities of VUEs with $N = 15$ RBs ([VI]©2018 IEEE).

4.2.5 Main results

In order to evaluate the performance of the proposed scheme, a Manhattan mobility model with various densities of vehicles is considered. The VUE pairs are distributed over the specified traffic lanes covering an area of 460×460 m^2. Each building is considered to be a fixed width of 200 m. Vehicles move along pre-defined bi-directional lanes with an average speed of 50 km/h. Minimum safety distance between the VUE's transmitter and VUE's receiver dynamically ranges from 15 m to 20 m. Traffic signals are emulated at each intersection area to prevent collisions among vehicles. The V2V line of sight (LOS) and non-line of sight (NLOS) WINNER+B1 channel model for the Manhattan layout is considered for path loss calculation [129]. To compare the proposed approach with 3GPP baseline [130] (*configuration* 1*, distributed scheduling*), each VUE pair optimizes its power over all RBs in every time slot. For considered baseline, all VUEs coordinates in distributed fashion to select the best possible resources for data transmission.

The tradeoff between the average power consumption and control parameter v as per (41) is shown in Fig. 18 for different densities of VUE pairs. When v is smaller, the VUE focuses on the rate maximization which consumes more power. In contrast,

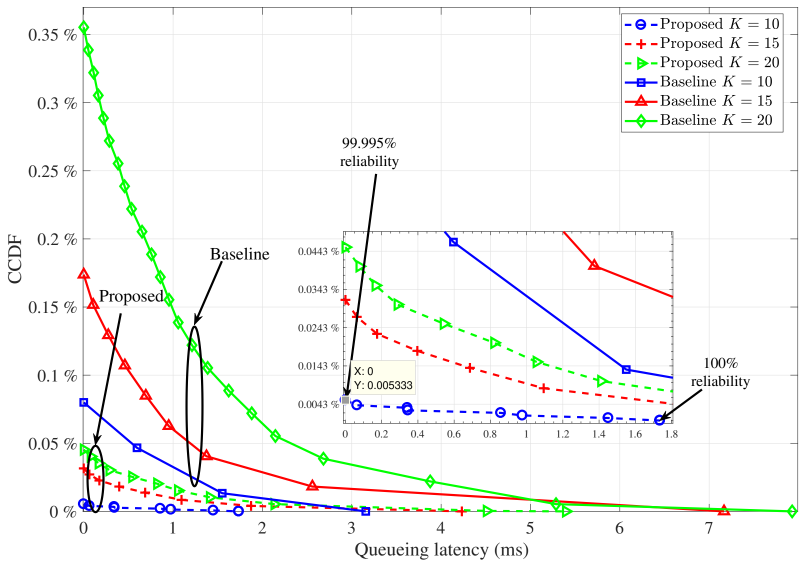

Fig. 19. CCDF of the instantaneous queuing latency for different densities of VUEs with fixed $V = 0$ and $N = 15$ ([VI]©2018 IEEE).

for a larger V, the VUE reduces its power consumption by allowing the queue length to grow. Fig. 18 also shows that the proposed approach yields significant reduction in power for higher values of v over the baseline approach. Subsequently, when V is smaller, each VUE will focus on rate maximization to decrease its queuing latency thus consuming more power. To scrutinize the transmission reliability via queuing latency, the complementary cumulative distribution function (CCDF) of the instantaneous queuing latency is investigated by assuming a fixed value of $V = 0$.

The reliability performance for varying VUE densities is shown in Fig. 19. It can be seen that, for different network settings, our approach always satisfies the aforementioned latency and reliability constraint (38b), (38c) while achieving a higher reliability performance (i.e., lower CCDF values) compared with the baseline. Furthermore, from Fig. 19, at 0.0053% of the CCDF value (i.e., 99.995% reliability) our proposed approach achieves a queuing latency reduction by up to 100%, 72%, and 60% for $K = 10, 15$, and 20, respectively, as compared to the baseline.

The results show the impact of parameters ε_k and L_k on the queuing latency. Fig. 20 shows the effect of ε_k for a fixed number of VUE pairs $K = 20$ and RBs $N = 15$. In order

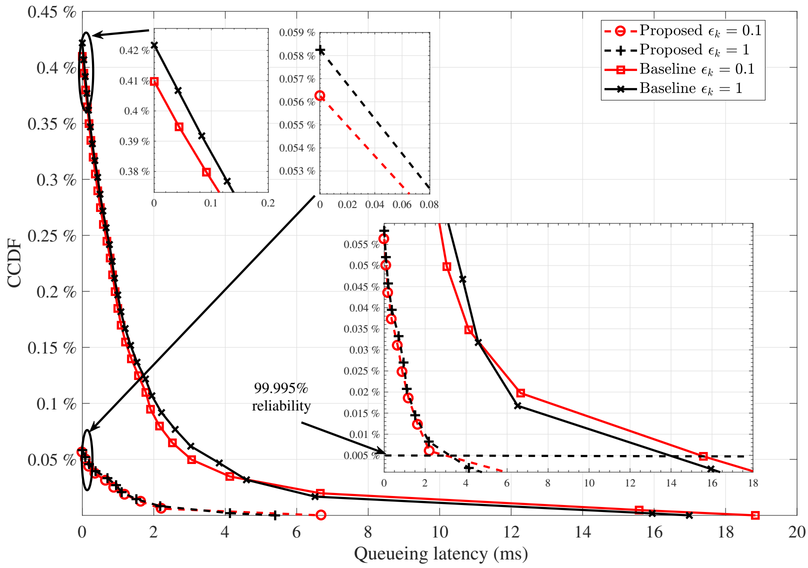

Fig. 20. CCDF of the instantaneous queuing latency for different ε_k with fixed $V = 0$, $N = 15$, $L_k = 2$, and $K = 20$ VUE pairs ([VI]©2018 IEEE).

to analyze the performance of queuing latency for different values of ε_k, considering the case $K > N$, for a fixed value of $L_k = 2$. Fig. 20 shows that, in order to achieve a 99.995% reliability (i.e., 0.0053% of CCDF) for different values of ε_k, the proposed approach reduces queuing latency as compared to the baseline by up to 80% and 77% for $\varepsilon = 0.1$ and 1.0, respectively.

5 Conclusions and future work

In this chapter, conclusions are drawn while emphasizing some future directions on 5G and beyond.

5.1 Conclusions

Next-generation wireless cellular networks need to address the growth in capacity demands driven by existing use cases as well as the proliferation of new types of devices, putting a strain on network operators. The integration of D2D communication into cellular networks is a promising solution for supporting the increasing demand for proximity-based applications and for enhancing the performance of next-generation networks. By allowing direct communication between mobile users, traffic can be offloaded from SCBSs to improve network coverage and throughput. This thesis addressed RRM challenges brought by the D2D-enabled SCNs and V2V communications. These challenges include interference management, user association, resource, and power allocations.

The main contributions related to D2D lie in the context of user association in SCNs exploring social ties among users in the network. However, the investigation on D2D-based V2V is still at an early stage and many issues, especially on medium access control (MAC) layer, need to be resolved before D2D can be efficiently used for challenging vehicular applications. Therefore, in this thesis, our main contribution related to V2V has been in the context of power control, frequency/time resource allocation while satisfying URLLC requirements.

In Chapter 2, the main challenges facing D2D communication in terms of inter-cell interference, device discovery, resource management, and user association are discussed. The first part of this thesis focuses on D2D user association problems while exploring the contextual information such as user's social ties, network connectivity, and other features to boost the network performance further. The thesis investigates challenges related to V2V communication. The classification and challenges of V2V communication are outlined. The main challenges dealing with V2V communication include interference management, resource management, and power allocation while ensuring reliability and latency constraints.

In Chapter 3, a novel social- and network-aware approach is proposed for user association in D2D underlaid SCNs. In particular, a novel user association framework is studied to address the following challenges: 1) How to locally distributes data while exploring different roles of nodes, 2) How to extract the social information, 2) How to define social-ties between users based on their common interest, 4) How to formulate the D2D links, based on the social-ties, 5) Selection of the important SN among social-aware D2D links, 6) How to coordinate interference among multiple D2D-enabled SCNs for load balancing, and 7) How to associate users to SN. The proposed approach allows to jointly exploit both the wireless and social aspects of wireless users to optimize the overall user association and improve traffic offloading in SCNs. The problem is formulated as a matching game with externalities in which the goal of each cluster of SCBSs is to maximize social welfare, which captures the data rates and peer effect due to social ties among UEs. A dynamic clustering approach is introduced to cluster SCBSs based on their distance and load similarities. In the proposed matching game, each UEs and SNs build their preferences and self-organize in their respective clusters as to choose their own utilities and achieve two-sided pairwise stable matching. To solve the proposed game, a social network-aware algorithm is presented in which UEs and SNs reach a stable matching in a reasonable number of iterations. Simulations results have shown that the proposed social network-aware approach provides considerable gains in terms of increased data rates compared to classical social-unaware approaches.

Chapter 4, exploits spatio-temporal information of vehicles for efficient resource allocation. In particular, a novel resource allocation framework is proposed for V2V networks to address the following challenges: 1) How to extract spatio-temporal characteristics of vehicles, 2) How to reduce control overhead and interference to other vehicles, 3) How to deal with the dynamic nature of vehicular networks, 4) How to extract channel information for resource allocation, 5) How to utilize the vehicles' traffic queue information, and 6) How to model the resource allocation problem considering URLLC requirements. A novel, dynamic proximity-aware resource allocation scheme for V2V communications is proposed. Above all, the proposed work aims to satisfy the requirements of V2V safety services while reducing the signaling overhead and interference from other pairs by enabling cluster formation. The problem is formulated as a matching game with externalities in which the VUEs and RBs build preferences over one another to minimize the overall network load. A new scheme for RB and power allocation in V2V communication is proposed while satisfying queuing latency and reliability constraints. To solve the latency- and reliability-aware resource allocation problem, a novel two-timescale resource allocation strategy is introduced: RSU groups VUEs in virtual clusters based on their spatial and temporal features over a longer timescale while a matching algorithm allocates RBs to each VUE based on their preference list at each time slot. Finally, using tools from Lyapunov optimization, every vehicle within a specific cluster optimizes its transmit power while satisfying prescribed reliability and queuing latency constraints.

5.1.1 Future work

The main focus of this thesis was to investigate and improve resource management for D2D-enabled SCNs and V2V networks. Specifically, first a social-aware user association is proposed for multi-cell SCNs considering *downlink* transmission. In addition, a frequency division duplex (FDD) scheme is used for D2D-enabled SCNs, and thus, it is interesting to study time division duplex (TDD) for such scenarios. Second, this thesis focuses on QoS-aware resource allocation for V2V considering a single-cell scenario, and thus, it is interesting to study how inter-cell interference management is required in a multi-cell environment. However, coexistence of cellular in presence of D2D and V2V communication can be interesting. There are several challenges and future perspectives that should be considered when designing new efficient D2D and V2V communication approaches for 5G, as outlined in the following.

Chapter 3 considers D2D communication only in *downlink* transmission assuming a synchronized co-channel multi-cell scenario. One interesting extension would be to investigate the interference problem in the multi-cell unsynchronized TDD technology scenario. Moreover, this thesis investigates user association and role selection in D2D networks. New methodologies to optimize *uplink/downlink* time, frequency, and spatial resources allocation need further investigation.

Chapter 4 focused on resource allocation strategies for single-cell V2V while satisfying latency and reliability requirements. Although the impact of interference introduced by multi-cells is neglected. It would be interesting to analytically derive feasibility conditions for the problem considering V2X in a multi-cell scenario. To increase the spectrum efficiency in future heterogeneous vehicular networks, one can think control information over the licensed band and data via V2V link (either using IEEE 802.11p or the licensed band). This approach increases the coverage and the capacity of future heterogeneous vehicular networks.

Exploring higher bands of 5G can be another option to offload cellular traffic and increase spectrum usage. In such scenarios, optimizing beamforming and beam steering with high mobility can be combined with adaptive learning mechanisms. For example, machine learning approaches can be one of the possible enablers for better resource management based on the trajectory of vehicles. However, other techniques such as multiple-input and multiple output (MIMO) can be of great interest both for mobile broadband and vertical scenarios. Furthermore, due to the increasing number of devices in future heterogeneous networks, overhead due to signaling and obeying security/privacy of these networks will be a significant concern. Therefore, new feasible control and secure communication protocols must be investigated while taking into consideration the unique characteristics of heterogeneous networks. Furthermore, next-generation networks are expected to promote diverse applications and enable seamless connectivity across multiple networks. Nevertheless, intelligent and ubiquitous access schemes are of great interest to support the coexistence of various wireless networks.

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ISBN 978-952-62-2461-9 (Paperback)
ISBN 978-952-62-2462-6 (PDF)
ISSN 0355-3213 (Print)
ISSN 1796-2226 (Online)