# Zusammenfassung

Es wird erwartet, dass die Nachfrage nach Proximity-Services (ProSe) in Mobilfunksystemen über das Jahr 2020 hinaus in verschiedenen Anwendungsbereichen stark ansteigen wird, z. B. im Bereich sozialer Apps und im Bereich öffentlicher Verkehrsmittel. ProSe bezeichnet Dienste zwischen Mobilfunkgeräten, welche sich in geografischer Nähe zueinander befinden und nach dem Durchlaufen einer sogenannten Entdeckungsphase lokal Informationen untereinander austauschen. Klassischerweise erfolgt in zellularen Netzwerken, z.B. 3G oder 4G, der Austausch von Informationen über die Basisstation zwischen den Endgeräten. Hierfür werden entsprechende Ressourcen für den Up- und den Downlink bereitgestellt. Im Vergleich dazu wird bei ProSe eine direkte Kommunikation zwischen zwei geografisch benachbarten Endgeräten ermöglicht, ohne die Informationen über die Netzinfrastruktur zu senden. Die Unterstützung von ProSe gilt als einer des wichtigsten technischen Wegbereiter für Mobilfunksysteme der nächsten Generation (5G). Der direkte Kommunikationsmodus, welcher auch als Device-to-Device (D2D)-Kommunikation bezeichnet wird, bietet gegenüber dem klassischen zellularen Modus eine Vielzahl an Vorteilen. Hierzu zählen insbesondere eine verbesserte spektrale Effizienz, eine bessere Leistungseffizienz sowie eine reduzierte Übertragungslatenz und eine Vergrößerung der Funkabdeckung. Innerhalb dieser Arbeit wird insbesondere untersucht, inwiefern durch die Anwendung von D2D-Kommunikation eine Steigerung der Leistungsfähigkeit und Effizienz von Mobilfunksystemen für die verschiedene Arten von ProSe erzielt werden kann.

Eine der Anforderungen an Mobilfunksystemen der fünften Generation ist, dass das übertragbare Datenvolumen im Vergleich zu den System der vierten Generation noch einmal deutlich gesteigert werder kann. Um diese Anforderung zu erfüllen, bietet die D2D-Kommunikation eine Möglichkeit zur Entlastung der zellularen Verbindungen, indem ein Teil des Datenverkehrs in einen lokalen Content-Sharing-Prozess ausgelagert wird. Dabei wird insbesondere der netzwerkgestützte Operationsmodus der D2D-Kommunikation, welcher durch das primäre zellulare System, z.B. Long-Term-Evolution (LTE), gesteuert wird und dessen Funkressourcen wiederverwendet, als eine Option zur Erhöhung der Systemkapazität betrachtet. Durch die Wiederverwendung der Funkressourcen der

zellularen Verbindungen durch D2D-Verbindungen tritt jedoch das Problem der gegenseitigen Interferenz auf. Daher ist es wichtig, effiziente Mechanismen einzuführen, um Interferenzen kontrollieren und minimieren zu können. Im Rahmen dieser Arbeit werden dazu netzwerkgesteuerte Radio Resource Management (RRM) Algorithmen mit geringer Berechnungskomplexität entwickelt, um die Ressourcenwiederverwendung zu optimieren. Diese werden hinsichtlich der relevanten Key Performance Indikatoren, z.B. Anzahl der unterstützten D2D Verbindungen, Systemkapazität und Benutzerzufriedenheit, untersucht. Um eine optimale Lösung für die entwickelten RRM-Algorithmen zu erzielen, werden zusätzlich Kontextinformationen berücksichtigt. Dazu werden in dieser Arbeit weiterhin Signalisierungsschemata mit geringem Signalisierungsaufwand entworfen. Mit Hilfe von numerischen Ergebnissen, welche aus Simulationen auf Systemebene (System Level Simulation) gewonnen wurden, wird die erzielbare Leistungssteigerung evaluiert.

Neben dem Ziel der Verbesserung der Servicequalität für Breitbanddienste der Klasse „Enhanced Mobile Broadband“ (eMBB) liegt der Fokus von 5G auch auf anderen neu entstehenden Diensten. Diese sind insbesondere Dienste im Bereich „Internet-of-Things“ (IoT), welche auch als „Massive Machine Type Communication“ (mMTC) bezeichnet werden und beispielsweise das Potenzial haben, neue Märkte für zukünftige Mobilfunknetze zu erschließen. Die Anforderungen der aufkommenden mMTC-Anwendungen können jedoch von den derzeitigen Mobilfunksystemen, z. B. LTE, nicht erfüllt werden, da diese in erster Linie für eMMB Dienste ausgelegt sind. Bisher wurde sowohl im wissenschaftlichen als auch im kommerziellen Bereich in Studien untersucht, inwiefern die Unterstützung für mMTC-Dienste durch eine Verbesserung und Anpassung der Mobilfunksysteme der vierten Generation ermöglicht werden kann. Die Herausforderungen dabei sind insbesondere, die Verfügbarkeit der Dienste zu verbessern und gleichzeitig den Energieverbrauch von mMTC-Endgeräten zu reduzieren. In dieser Arbeit wird dazu ein netzwerkgesteuertes Sidelink-Kommunikationsschema erarbeitet, welches unter Heranziehung von verschiedenen Kontextinformationen die Effizienz von mMTC-unterstützen Mobilfunknetzen erhöht. Mit Hilfe der Kontextinformationen kann eine intelligente Konfiguration sowohl für die direkte als auch für die zellulare Verbindung ermöglicht werden. Zur Akquisition der dazu relevanten Kontextinformationen wird eine entsprechende aufwandsarme Signalisierung entworfen. Dazu wird im Rahmen dieser Arbeit weiterhin ein Simulator implementiert, um die vorgeschlagenen Konzepte sowohl in Szenarien mit eine einziger Mobilfunkzelle als auch mit mehreren Zellen zu evaluieren. Die Simulationsergebnisse zeigen dabei, dass durch die vorgeschlagenen Lösungsansätze gleichzeitig sowohl die Serviceverfügbarkeit als auch die Energieeffizienz von mMTC-Endgeräten verbessert werden kann.

Eine weitere Diensteklasse in zukünftigen zellularen Systemen sind Dienste, welche den Informationsaustausch zwischen verschiedenen Verkehrsteilnehmern ermöglichen. Diese werden auch als „Vehicle-to-Everything“ (V2X)-Kommunikation bezeichnet und haben als ein Ziel, den Automatisierungsgrad in Fahrzeugen durch entsprechende Anwendungen zu erhöhen, beispielsweise um Unfälle zu vermeiden oder eine Verbesserung der Verkehrseffizienz zu erzielen. Um diese Anwendungen zu unterstützen, sind eine extrem hohe Zuverlässigkeit und eine niedrige Übertragungslatenz erforderlich, welche für die Kommunikationstechnologien der vorherigen Generation (z. B. LTE) technisch sehr herausfordernd sind. Im Rahmen dieser Arbeit werden zunächst die beiden Funkschnittstellen LTE-Uu für zellulare Verbindungen mit involvierter Netzwerkinfrastruktur zur Übertragung des V2X-Datenverkehrs und PC5 für Übertragung des V2X-Datenverkehrs über direkte Verbindungen zwischen Endgeräten untersucht, welche vom 3rd Generation Partnership Project (3GPP) als mögliche Technologien vorgeschlagen wurden, um V2X-Kommunikation zu ermöglichen. Eine weitere Anforderung an diese Technologien ist eine große Reichweite für V2X-Kommunikation aufgrund der hohen Geschwindigkeiten von Fahrzeugen, bspw. auf Autobahnen. Dies kann mit einer einzigen Paketübertragung (Single Hop) eines Senders über die direkte Funkschnittstelle nicht erreicht werden. Daher wird in dieser Arbeit ein kontextsensitives V2X-Kommunikationsschema eingeführt, bei welchem einige Fahrzeuge ausgewählt werden, um als Relais zu fungieren und ihre empfangenen Pakete erneut an andere Fahrzeuge zu senden. Dies ermöglicht auch eine Datenübertragung, obwohl sich die Empfänger möglicherweise außerhalb der Reichweite des ursprünglichen Senders befinden (Two Hop Übertragung). Mit diesem Ansatz können sowohl die Reichweite als auch die Zuverlässigkeit der ent-

sprechenden Paketübertragung im Rahmen der V2X-Kommunikation erhöht werden. Die jeweiligen Funkressourcen dieser beiden Übertragungen werden dabei basierend auf der Lösung des zugehörigen Optimierungsproblems zugeordnet. Eine weitere Anforderung von V2X-Services ist die Gewährleistung einer extrem hohen Zuverlässigkeit, welche in einigen Szenarien nicht mit einer einzigen Übertragungstechnologie, beispielsweise LTE-Uu oder PC5, erfüllt werden kann. Daher wurde in diesem Zusammenhang untersucht, inwiefern diese Anforderung durch das gleichzeitige Nutzen zweier oder mehrerer Funktechnologien, was auch als „Multi Radio Access Technology“ (Multi-RAT) bezeichnet wird, erfüllt werden kann. Um das Multi-RAT Konzept auf effiziente Weise anzuwenden, werden verschiedene Multi-RAT-Verfahren entworfen und verglichen. Dabei wird auch das klassische Uplink-Konzept für den Fall erweitert, dass eine Basisstation V2X-Datenpakete sowohl von der LTE-Uu- als auch von der PC5-Schnittstelle empfangen kann. Für den Downlink werden zur Verbesserung der Übertragungszuverlässigkeit verschiedene Multicast-Broadcast-Single-Frequency-Network-(MBSFN)-Area-Mapping-Ansätze entwickelt.

**Schlagwörter -** 5G-Funkzugangsnetz, Proximity-basierte Dienste, Geräte-zu-Gerät-Kommunikation, massive Maschinentyp-Kommunikation, Vehicle-to-Everything-Kommunikation, Bewertungsmethodik

# Abstract

It is commonly expected that there will be an evolving demand for proximity-based services (ProSe) in different application areas for the time beyond 2020, e.g. social apps and public transportation. ProSe denotes services requiring a direct discovery and communication among mobile devices that are geographically located near each other. In this sense, a local information exchange is required to support the ProSe. In legacy cellular networks, e.g. 3G and 4G, this procedure is realized by transmitting data traffic through a base station via uplink and downlink. In contrast to that, a direct communication mode not transmitting data traffic through any network infrastructure is referred to as sidelink communication. It has been considered as one of the key technical enablers for the next generation of mobile communications systems (5G), especially from the perspective of supporting ProSe. With the direct communication mode, a direct device-to-device (D2D) communication can be applied with certain benefits, e.g. an improved spectral efficiency, a better power efficiency, a reduced latency, and an extended coverage area.

In this thesis, the author investigates and develops how to efficiently apply the direct communication mode to improve the performances of different 5G service types, i.e. enhanced Mobile Broadband (eMBB) service, massive Machine Type Communication (mMTC), and Vehicle-to-Everything (V2X) communication. In particular, context-aware algorithms are developed to optimize network configurations. Moreover, in order to support the proposed direct communication technologies, corresponding signaling schemes are designed. Last but not least, simulations are conducted to evaluate the proposed schemes quantitatively.

**Keywords -** 5G Radio Access Network, Proximity-based Services, Evaluation Methodology, Device-to-Device Communication, massive Machine Type Communications, Vehicle-to-Everything Communication

# Chapter 1 Introduction

## 1.1 Motivation

In the past decades, wireless communication systems [Lin06, TV05, Wal99, Stu96] have made a rapid progress and are replacing the use of wired networks. Moreover, the services supported by wireless networks tend to become more and more diverse, e.g. covering both human-driven and machine-type services. The next generation of mobile communication system (5G) aims at providing enhanced human-dominated wireless communications as well an all-connected world of humans and objects [OMM16]. For example, 5G should enhance its mobile broadband (MBB) services with a better quality of service (QoS) compared with the legacy cellular systems [OBB+14], e.g. the third generation of mobile communication system (3G) and the fourth generation of mobile communication system (4G) [DPSB10, SBT11, HT07, HMCK05]. Moreover, there is a broad consensus that 5G will not only be a simple evolution of the 4G network with a higher spectral efficiency and a higher peak throughput, but also targets new services and business models [EMM+18]. As a typical 5G use case, in massive Machine Type Communications (mMTC) scenarios, a large amount, e.g. 300,000 machine-type devices (MTDs) within one cell [OBB+14] are expected to be connected with the network. For instance, in order to track objects in logistics, tags are attached to the objects and they need to be equipped with the capability for transmitting their location information to the network. Another typical example refers to agriculture applications, where low-cost sensors are distributed in rural areas to monitor the environment. In addition to the MBB and mMTC use cases, 5G will also provide support for the Ultra-Reliable Low Latency Communications (URLLC), where a low latency. e.g. 5 ms [OBB+14] and high reliability, e.g. 99.999% [OBB+14], are desired. One exemplary application which falls into this category is the automatic driving, which aims at better traffic safety and efficiency.

As a key technology component in 5G, the direct Device-to-Device (D2D) communication can facilitate a direct communication among nearby devices without transmitting data traffic through a network infrastructure. In this thesis, the author will focus on its design and application in the radio access network (RAN) to improve system performance w.r.t. different types of services envisioned in 5G, i.e. enhanced Mobile Broadband (eMBB), mMTC and URLLC. It is worth noticing that the term "sidelink (SL)" in the 3rd Generation Partnership Project (3GPP) refers to a direct radio link between two arbitrary devices over an interface called PC5 and, therefore, currently comprises the low radio protocol layers, i.e. up to the packet data convergence protocol (PDCP) layer. However, the term "D2D communication" normally refers to an end-to-end (E2E) application. In addition, another focus of this thesis is the exploitation of the relevant context information, e.g. channel state information (CSI), user equipment (UE) location, UE-specific QoS requirement, service priority, battery level, [SKMS12, MKSS11, MSKS11, KRSS14, MSC+13] that is beneficial for enhancing the performance of D2D operation.

In the eMBB use case of 5G, the mobile data volume per area is expected to be 1000 times and the user data rate 10 to 100 times higher than those provided by legacy 4G system. In order to fulfill these requirements, different techniques have been proposed for 5G. For instance, the feasibility of dedicating more spectrum resource to operators for providing eMBB services has been discussed, especially in the frequency range up to 60 GHz [LTRa+18], which is part of the millimeter wave band. Moreover, network infrastructure densification has also been considered to increase the spatial reuse of system resources and, therefore, improve the data volume per area and the user data rate [CQH+16, GSA16]. However, these solutions require more financial investment from mobile network operators (MNOs). In comparison, D2D communication with an underlaying mode has the potential to enable a spatial reuse of spectral resources without purchasing new spectrum or access points. In the D2D underlaying mode, D2D communication operates on the same resource as cellular communication at the same time [MRA17]. Specifically, it is favored to reuse the cellular uplink resource compared with the cellular downlink resource, since the uplink resource is often less utilized and the cellular pilot and synchronization signals are always transmitted in the downlink [LAGR14]. On the other hand, a critical design problem of D2D communication in the underlaying mode is the mutual interference between the two links using the same resource. In this thesis, a network-controlled sidelink communication taking account of context information is developed to manage the radio resource allocation and mitigate the mutual interference. In 5G, context information needs to be identified from different sources, e.g. a UE and a BS, and it will act as a key to support an efficient radio resource management (RRM) [MET17c]. As mentioned before, the exploited context information in this thesis includes CSI, UE location, UE-specific QoS requirement, service priority, battery level, etc.

Currently, there are multiple factors that demand an increased number of connected MTDs: The smart-grid, large-scale environment and structure monitoring, asset and health monitoring, etc [BPW+18]. Since the MTDs in these applications only sporadically transmit small data packets to the network, they do not consume large data volume capacity. However, due to the characteristics of mMTC applications, the QoS requirements are divergent from the human-type services. For instance, it is predicted to have tens of billions of MTDs beyond 2020. Thus, how to provide such a massive connectivity by the cellular network is an important research question. Moreover, the new levels of availability and power efficiency requirements for mMTC pose technical challenges on the RAN. Thus, 3GPP has conducted research to evolve the legacy 4G system to cover this new type of services. For example, in order to reduce the implementation cost of an MTD, 3GPP has proposed a new type of UE, i.e. the UE category 0 in [3GP16d], where both bandwidth and peak data rate are reduced. Moreover, the costs of the power amplifier (PA) can be reduced by limiting the maximal transmit power [3GP13c]. However, any reduction in transmit power can introduce a negative impact on the network coverage. In order to maintain a good coverage, other technologies, e.g. narrow band transmission and massive transmission time interval (TTI) bundling [3GP15a], have been proposed, but they introduce a large battery drain at an MTD. Therefore, in this thesis the author investigates how to improve network coverage and meanwhile improve power efficiency for mMTC by exploiting sidelink communication.

As another significant aspect envisioned in 5G, Vehicle-to-Everything (V2X) communication is considered as a typical application of URLLC due to its required low latency and ultra-high reliability. Since V2X communication also refers to a local information exchange procedure in most of the cases, it can be deemed as a special type of D2D communication. However, the relevant users in V2X communication are only traffic participants, and its main goal is to improve traffic safety and efficiency beyond 2020 [MET13a]. To be more specific, V2X communication includes different communication profiles such as Vehicle-to-Vehicle (V2V), Vehicle-to-Pedestrian (V2P), Vehicle-to-Infrastructure (V2I) and Vehicle-to-Network (V2N) communications. Since the legacy 4G system is not capable of providing a reliable V2X communication, e.g. reliability of 99.999%, with a low packet E2E latency, e.g. 5 ms, both academia and industry are working together to design the 5G system to support different automated driving applications including vehicle platooning, advanced driving, remote driving, and sensor information sharing [SJD+18]. For instance, efforts have been made in recent years to offer V2X communication by the 802.11p protocol standardized by the Institute of Electrical and Electronics Engineers (IEEE) [IEE10]. Since the IEEE 802.11p protocol operates in a decentralized mode, there is no central entity to coordinate the transmissions of different users. In order to support this decentralized mode, the medium access control (MAC) layer of the IEEE 802.11p protocol applies a carrier-sense multiple access with collision avoidance (CSMA/CA) scheme that cannot guarantee strict reliability in the case of a high system load. Comparing to the decentralized mode, the 5G system can coordinate the transmissions from different users and, therefore, it has the potential to offer better reliability. So far, two air interfaces have been considered as candidates to support V2X communication in the cellular network, i.e. the LTE-Uu and the PC5 interfaces. In this thesis, the feasibility of applying these two interfaces in V2X communication is examined. This work also improves the communication reliability by proposing a network-controlled two-hop V2X communication and a multi-radio access technologies (multi-RAT) concept.

It is worth noticing that 3GPP has standardized four transmission modes (mode 1-4) for the PC5 interface to support different types of proximity-based services (ProSe). For instance, to support the public safety services, the structure of the physical uplink shared channel (PUSCH) is re-used for sidelink transmission modes 1 and 2. However, for the vehicular applications to improve traffic safety and efficiency, both modes 1 and 2 are not suitable [MMG17] due to the high user mobility. Thus, to cope with V2X communication, the V2X sidelink transmission modes 3 and 4 have been standardized in 3GPP by modifying the relevant functions in modes 1 and 2. For instance, additional demodulation reference signals (DMRS) have been added to the physical layer to handle the high Doppler associated with the relative speeds of up to 500 km/h [3GP18d]. Specifically, both transmission modes 1 and 3 require a radio resource being scheduled by the network, while modes 2 and 4 have been designed to facilitate a UE-autonomous radio resource selection approach.

## 1.2 Objectives of the thesis

In practical terms, the following list depicts the prime aspects that this thesis copes with:

1. **Network-controlled sidelink communication in the eMBB use case to offload network traffic**: To develop efficient RRM algorithms for allocating radio resources to both the cellular and underlaying D2D links. In order to optimize system performance, context information should be collected with a reasonable signaling effort and correspondingly taken into account by the RRM algorithms.

2. **Applying network-controlled sidelink communication in the mMTC use case to improve network coverage and device power efficiency**: To simultaneously enhance UE power efficiency and extend network coverage by employing sidelink communication among MTDs that are in the proximity of each other. The principal issues to be solved here include how to assign different transmission modes (TMs), e.g. cellular, relay and sidelink modes, to different MTDs and how to design the corresponding control-plane (CP) procedures such as signaling schemes.

3. **Network-controlled V2X communication to provide a low E2E latency and high reliability**: To inspect V2X communication under the scope of cellular technologies. In a cellular network, V2X communication can be realized by either transmitting data packets through network infrastructures, i.e. via the LTE-Uu interface, or a direct V2X communication, i.e. via the PC5 interface.

Thus, both approaches need to be investigated to analyze their pros and cons. Moreover, since the ultra-high reliability requirement in V2X communication cannot always be satisfied by using a single-RAT or a single-hop V2X communication, this work should enhance the communication reliability with new technical proposals, e.g. a multi-RAT V2X communication and a two-hop V2X communication.

Last but not least, in order to obtain a quantitative understanding of the achievable performance gains, the proposed schemes should be implemented and evaluated in a simulation platform which is able to reflect the real world scenarios.

## 1.3 Contributions of the thesis

The contributions of D2D communication in this work can be structured w.r.t. different types of services in 5G, i.e. eMBB, mMTC and V2X. Please note that the direct communication mode is first introduced in the 3GPP release 12, and it is also considered as a technology for 5G network [MET14a]. Thus, the developed technology in this thesis provides a technical design of D2D communication for the 5G RAN. The concepts and algorithms described in this thesis represent the main contributions of the author to the European FP7 project METIS, Horizon 2020 project METIS-II, and the German BMBF project 5G NetMobil developed between 2013 and 2018. The majority of this research work was conducted, when the initial 5G standard had not been defined. In order to inspect the D2D communication from a system level perspective, the author cannot develop every function and, therefore, some concepts from the legacy cellular LTE network are reused by this work as reference in evaluation. For instance, the link-level performance of the LTE air interface is reused in this thesis. For investigations on the performance improvement of D2D communication, the Long Term Evolution (LTE) technology, e.g. 3GPP Release 12, is considered as a reference. In essence, the research activities carried out in this thesis focus on the 5G CP design, and the LTE functionalities have been reused to generate the user-plane (UP) performance. Moreover, since 5G targets at a control and user plane split that allows an independent evolution of the CP and UP functions [MET17b], the developed concepts and algorithms in the

CP can also be applied in future cellular systems with further evolution on UP functions.
Moreover, since the evaluation methodologies for the legacy 4G system were proposed to evaluate the performance of human-type services, the evaluation framework is adjusted and extended to cover the new service types in this thesis, e.g. mMTC and V2X. In the following, the detailed contributions of this thesis will be categorized w.r.t. the service types.

### 1.3.1 Network-controlled sidelink communication to offload network traffic

This work

- proposes mathematical models to optimize system performances w.r.t. the number of established D2D links, system capacity, and user satisfaction,
- develops heuristic RRM algorithms with low complexity to solve the constructed optimization problems,
- improves the efficiency of the RRM algorithms by exploiting context information, e.g. channel state information, UE-specific data rate requirement, service priority, and user location,
- designs corresponding signaling schemes to support the proposed sidelink communication and collect the required context information with a reasonable signaling effort.

### 1.3.2 Applying network-controlled sidelink communication in the mMTC use case

This work

- applies multiple clustering schemes for grouping mMTC devices to ensure any two mMTC devices forming a D2D link are not far away from each other,
- develops a smart TM selection approach to configure relay and remote UEs in each cluster by using context information, e.g. sensor location and the real-time battery level,

- designs signaling schemes to both collect the relevant context information and enable the proposed sidelink communication that improves the network coverage and energy consumption of MTDs.

### 1.3.3 Network-controlled V2X communication

This work

- introduces how to apply a cellular V2X communication through network infrastructures, i.e. via the LTE-Uu interface, and a direct V2X communication, i.e. via the PC5 interface,
- develops the methodology to evaluate the V2X communication,
- evaluates the performance of both the cellular V2X communication via the LTE-Uu and the direct V2X communication via the PC5 (the performance can be considered as a baseline to evaluate new technical proposals in the future),
- proposes a network-controlled two-hop V2X communication via the PC5 interface to increase the communication reliability in the case that a large V2X communication range is required,
- optimizes the resource allocations to the first hop and the second hop in order to achieve a maximal packet transmission range for the proposed two-hop V2X communication,
- explains how to collect and exploit context information to make the proposed two-hop V2X communication more efficient,
- designs a multi-RAT concept to enhance V2X communication by transmitting data packets via both the LTE-Uu and the PC5 interfaces,
- proposes to equip base stations (BSs) with the capability to receive packets from UEs via the PC5 interface in order to achieve a better robustness in uplink transmission.

### 1.3.4 Performance evaluation of D2D and V2X communications

This work

- proposes an evaluation framework for ProSe w.r.t. different service types, i.e. eMBB, mMTC and V2X,
- implements the system-level simulators in MATLAB to derive the performances of the proposed technologies,
- quantitatively evaluates the performance gains of D2D and V2X communications in terms of different key performance indicators (KPIs), e.g. system capacity, number of established D2D links, device battery life, network coverage, packet E2E latency, etc,
- validates the benefits of applying direct D2D operation, including an increased spectral efficiency, an enlarged network coverage, a better UE power efficiency, a lower E2E latency, and higher communication reliability.

## 1.4 Relevant publications

The contributions of the thesis were published in various peer-reviewed magazine, journal and conference papers, and also in two book chapters. The publication list for the topic on exploiting a network-controlled sidelink communication to offload network traffic includes [JKK+14, JKKS14, JWKS17, SJD+18]. The work related with the network-controlled sidelink communication in the mMTC use case is published in [JLS17, JHLS17, SJD+18]. In addition, [JLWS17, JWHS17, JWHS18b, JDWS18, JWHS18a] contain the relevant work of the network-controlled V2X communication. Moreover, part of the 5G evaluation framework w.r.t. different use cases has been captured in [MFMSJ16]. Last but not least, the publications of the author in [SKJ+15, KKJ+15, JT13, TJ14, WKJS17, RJKS15, SJMS13, KWJS18, HJS18] also comprehensively contribute to a better understanding of the topics addressed in this thesis.

## 1.5 Organization of the thesis

This thesis is organized as follows:

1. The author first presents the state-of-the-art evaluation methodology of the legacy 4G system in Chapter 2 and discusses how to extend and modify the legacy evaluation framework for assessing

the technical D2D and V2X communication proposals in the 5G system. After that, the author provides detailed descriptions regarding the simulation models that will be used and implemented in the following chapters to evaluate the technical proposals.

2. In Chapter 3, a context-aware network-controlled sidelink communication concept is introduced to offload traffic from cellular communication to local communication. In this chapter, the author designs multiple RRM algorithms to optimize network performance w.r.t. different targets, e.g. the maximal number of established D2D links and system capacity. Moreover, in order to offer the eMBB services with different QoS requirements, e.g. data rate and priority level, to the mobile users, context information is taken into consideration by the proposed RRM algorithms. Please note that at the beginning of this chapter only CSI is used to derive the context-aware RRM algorithm. Though a context-aware scheme usually does not only apply the CSI, it is exploited as a starting point, and other context information, e.g. UE location, UE data rate requirement, and service priority, is taken into account by the RRM algorithms in the later part of this chapter. In addition, to support the RRM algorithms and collect the required context information, signaling schemes in both single-cell and multi-cell scenarios are designed in this chapter. Further, the performance of the proposed algorithms are simulated, and their results are compared with other baseline schemes.

3. Chapter 4 deals with how to exploit sidelink communication to improve the UE energy consumption and the network coverage simultaneously in the mMTC use case. In order to assist a BS for pairing a remote sensor with an appropriate relay sensor, the sidelink configuration task is decomposed into two sub-tasks, i.e. device clustering and TM selection in this chapter. Correspondingly, three essential signaling schemes are also introduced to initialize sensor attachment, update TM, and transmit uplink report via sidelink communication. Finally, simulation results obtained from both the urban and the rural areas are given and analyzed.

4. At the beginning of Chapter 5, the two different approaches of realizing V2X communication using the LTE-Uu air interface and the

PC5 air interface are investigated. Following that, a concept of network-controlled two-hop V2X communication via the PC5 interface is proposed to meet the high-reliability requirement of the V2X communication in a large communication range. In this part, the author also shows that the transmission range of data packets can be maximized by adjusting the amount of resources allocated to the two different hops. Moreover, context information is collected and applied to configure relay vehicles for the second hop transmission. In addition, a multi-RAT scheme is also developed in this chapter to achieve a diversity gain, since using one single-RAT might not always fulfill the reliability requirement. This proposal enables data transmission through both the cellular network infrastructures, i.e. via the LTE-Uu, and a direct V2X communication, i.e. via the PC5 interface. In the last part of this chapter, the numerical results provide a deep insight into the performance comparison of the different V2X communication technologies.

5. In Chapter 6, the author concludes the contributions of this thesis and outlines the possible areas of future work on D2D and V2X communications.

# Chapter 2
# Evaluation Framework and Methodology

## 2.1 Evaluation methodology for 4G

The legacy 4G system was designed to mainly serve human-driven traffic, and it provides a better user experience compared with the previous cellular systems, e.g. 2G and 3G. The performance metrics typically defined for a 4G system include cell spectral efficiency, peak data rate, bandwidth scalability, cell-edge user spectral efficiency, latency, handover interruption time, and VoIP capacity [IR08b].
In order to set a common criterion for different organizations to evaluate the performance of different 4G technical candidates, the ITU Radiocommunication Sector (ITU-R) has come up with a guideline document in [IR08a] with considerations from different perspectives, e.g. vendors, network operators, device manufacturers, and service and content providers. Moreover, as the most interesting part for simulation experts, [IR08a] also describes the system simulation procedures, e.g. deployment model, traffic model, mobility model and channel model, and the evaluation methodologies to derive the performance of different KPIs.
In principle, the KPIs can be categorized into three main classes by looking at the approaches applied for their evaluation [WWLS10, SZJ+09, Ahm10]:

- KPIs to be analytically evaluated, e.g. intra-/inter frequency handover interruption time, peak data rate, peak spectral efficiency, and control/user plane latency,
- KPIs to be inspected by examining the protocol designs and checking if certain features are supported, e.g. inter-system handover,
- KPIs to be evaluated with simulation, e.g. cell/cell-edge user spectral efficiency, VoIP capacity, mobility.

### 2.1.1 Analysis-based and inspection-based KPI evaluation

The performance of the analysis-based KPIs can be calculated based on the RAT specifications [Oss11]. For instance, the peak data rate can

be calculated by extracting the overhead, e.g. synchronization and reference signals, from the maximal data bits per time unit. Moreover, in order to check whether the CP and UP latency of a technical proposal comply with the requirements specified for International Mobile Telecommunications-Advanced (IMT-Advanced) systems, the calculations for both the frequency-division duplex (FDD) and the time-division duplex (TDD) modes are given in [SKC10]. In addition, to inspect how well a cellular system can support user mobility, the handover interruption time should be derived. This can be done by dividing the whole handover procedure to different technology-specific delay components and computing the summation of their values [SKC+11]. Since a relay concept has been studied and introduced in 3GPP Release 9, the cell spectral efficiency of a relay-enhanced cell deployment scenario can also be calculated using the methodology defined in [BAS10].
In the other cases where an inspection method is applied, the corresponding KPIs are evaluated by inspecting the system design information, e.g. protocol and architecture design, and the assessment of these KPIs requires only a Yes/No answer. For instance, by inspecting the network interoperability design between 4G and 3G, it can be seen whether an inter-system handover is feasible to avoid dropping of a call when a mobile device enters the coverage area of a 3G system from a 4G system.

### 2.1.2 Simulation-based KPI evaluation

In the simulation-based approach, the KPIs need to be derived by running a simulator taking account of the different features in the relevant protocol layers, e.g. modulation and coding scheme (MCS), hybrid automatic repeat request (HARQ), and scheduling. Moreover, in order to reduce computational complexity, a mapping table from signal-to-interference-plus-noise ratio (SINR) to block error rate (BLER) should be generated from a link-level simulator and integrated into a system level simulator [HS13]. Moreover, to precisely reflect the characteristics of a radio link, e.g. frequency-selective fading, a link-to-system (L2S) level mapping needs to be accurately formulated. In literature [BAS+05], two metrics have been widely used to construct the L2S level mapping, i.e. the exponential effective SINR metric (EESM) and the mutual information effective SINR metric (MIESM). Due to a reduced complexity to