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ÚSTAV TELEKOMUNIKACÍ

HETEROGENEOUS CONNECTIVITY OF MOBILE DEVICES IN 5G WIRELESS SYSTEMS

HETEROGENNÍ PROPOJENÍ MOBILNÍCH ZAŘÍZENÍ V BEZDRÁTOVÝCH SYSTÉMECH 5. GENERACE

DOCTORAL THESIS
DIZERTAČNÍ PRÁCE

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ABSTRACT

This dissertation thesis addresses the "Heterogeneous Connectivity of Mobile Devices in 5G Wireless Systems". Despite decisive progress in many enabling solutions, next-generation cellular deployments still suffer from a glaring lack of bandwidth due to inefficient utilization of radio spectrum, which calls for immediate action. The main aim of this Ph.D. work is to propose novel mechanisms providing proximity-based (cellular-assisted) networking and communication algorithms for dynamic allocation of spectrum resources in fifth-generation (5G) systems. Proposed communication mechanisms are comprehensively evaluated by the developed simulation tools (calibrated with the 3GPP data sets) as well as within the experimental 3GPP LTE-A cellular deployment at Brno University of Technology (BUT), Czech Republic. Obtained practical results (supported by novel mathematical analysis in characteristic scenarios) become instrumental to facilitate more dynamic bandwidth sharing. Thus, they promise to improve the degrees of spectrum utilization in future 5G systems without compromising the service quality and user experience (QoS and QoE) across different applications. As the main output of this thesis, particular research findings contributed in part to the 3GPP Release 12 specifications.

KEYWORDS

5G, Cellular Systems, Device-to-Device (D2D) communication, Dynamic Spectrum Allocation, Internet of Things, Licensed Shared Access, Machine-to-Machine, Networking, Proximity-based communication.

ABSTRAKT

Předkládaná disertační práce je zaměřena na "heterogenní propojení mobilních zařízení v bezdrátových systémech 5. generace". Navzdory nepochybnému pokroku v rámci navržených komunikačních řešení postrádají mobilní sítě nastupující generace dostatečnou šířku pásma a to hlavně kvůli neefektivnímu využívání rádiového spektra. Tato situace tedy v současné době představuje řadu otázek v oblasti výzkumu. Hlavním cílem této disertační práce je proto návrh nových komunikačních mechanismů pro komunikaci mezi zařízeními v bezprostřední blízkosti s asistencí mobilní sítě a dále pak návrh a implementace algoritmů pro dynamické přidělování frekvenčního spektra v nastupujících mobilních sítích 5G. Navrhnuté komunikační mechanismy a algoritmy jsou následně komplexně vyhodnoceny pomocí nově vyvinutých simulačních nástrojů (kalibrovaných s využitím 3GPP trénovacích dat) a zejména pak v experimentální mobilní síti LTE-A, která se nachází v prostorách Vysokého učení technického v Brně, Česká Republika. Získané praktické výsledky, které jsou podpořeny zcela novou matematickou analýzou ve speciálně navržených charakteristických scénářích, představují řešení pro vlastníka spektra v případě požadavků na jeho dynamické sdílení. Tato metoda tedy představuje možnost pro efektivnější využití spektra v rámci mobilních sítí 5G bez degradace kvality služeb (QoS) a kvality zážitků (QoE) pro koncové uživatele. Vědecký přínos dosažených výsledků dokazuje fakt, že některé z principů představených v této disertační práci byly zahrnuty do celosvětově uznávaného standardu (specifikace) 3GPP Release 12.

KLÍČOVÁ SLOVA

5. Generace mobilních sítí, Dynamické alokování spektra, Internet věcí, Komunikace mezi stroji, Komunikace zařízení v bezprostřední blízkosti, Přímá komunikace mezi zařízeními, Sdílený přístup k licencovanému spektru, Síťová komunikace.

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DECLARATION

I declare that I have written the Doctoral Thesis titled "Heterogeneous Connectivity of Mobile Devices in 5G Wireless Systems" independently, under the guidance of the advisor and using exclusively the technical references and other sources of information cited in the thesis and listed in the comprehensive bibliography at the end of the thesis.

As the author I furthermore declare that, with respect to the creation of this Doctoral Thesis, I have not infringed any copyright or violated anyone's personal and/or ownership rights. In this context, I am fully aware of the consequences of breaking Regulation § 11 of the Copyright Act No. 121/2000 Coll. of the Czech Republic, as amended, and of any breach of rights related to intellectual property or introduced within amendments to relevant Acts such as the Intellectual Property Act or the Criminal Code, Act No. 40/2009 Coll., Section 2, Head VI, Part 4.

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The research work described herein has been conducted at Department of Telecommunications, Faculty of Electrical Engineering and Communication, Brno University of Technology over the years 2013 - 2017. This manuscript is to the best of my knowledge original, and neither this nor substantially similar dissertation thesis has been submitted at any other university. As financial stability is fundamental for all researchers, I would like to acknowledge the generous support received from grants of Brno University of Technology which allowed me to pursue Ph.D. study.

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INVESTICE DO VAŠÍ BUDOUCNOSTI

OP Výzkum a vývoj pro inovace

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1 INTRODUCTION

1.1 Research Motivation

At the time, when G. Marconi, an Italian inventor, opened the path of recent day wireless transmissions by communicating the letter "S" as electromagnetic waves along a distance of 3 kilometers as a three-dot Morse code, the new era of wireless communications has begun. After this exceptional breakthrough, wireless communication has started to be key part of present society providing the ubiquitous connectivity [1].

It was not more than a few decades since mobile wireless communications were introduced with the first generation (1980's) – voice-only communication systems. Over the last couple of decades the world has witnessed gradual, yet steady evolution of mobile wireless communications towards second (circuit switching systems), third (utilizing both circuit and packet switching systems), fourth and now fifth generation (all-IP) wireless networks, which are using packet switching. Along with mentioned factors, approaches also differentiate between licensed spectrum and unlicensed spectrum [2]. Looking back to the history, all four recent generations of cellular systems have been evolved over approximately 10-year intersecting cycles and therefore, many expect that the next major evolution in wireless communications – the 5th generation – will be implemented and fully deployed around 2020 and beyond [3].

Any massive real-world deployment is always preceded by thorough research stage and since we, as a research society, are currently around four years prior to the expected roll out of next-generation 5G mobile systems, it is not surprising that 5G is the most turbulent topic among research community nowadays with hundreds of scientific articles indexed by international databases every year. The key of such extreme interest lies in the anticipated revolutionary character and high heterogeneity of the future 5G network's architecture combining the aspects of emerging ultra-high-frequency spectrum access, hyper-connected vision, new application-specific requirements and much more [2].

A quick look into recent wireless network statistics reveal that global mobile traffic grew 63 % in 2016 and almost half a billion (429 million) mobile devices and connections were added in 2016 [4]. Globally, smart devices represented 46 % of the total mobile devices and connections in 2016; they accounted for 89 % of the mobile data traffic. Another interesting finding is that smartphones represented only 45 % of total mobile devices and connections in 2016, but represented 81 % of total mobile traffic. Cisco's Visual Networking Index (VNI) forecasts that by 2021, nearly three-quarters of all devices connected to the mobile network will be "smart" [4].

Based on the above mentioned facts, 5G is introducing a breakthrough shift, barely comparable with previous generations, based on completely new technologies and brilliant innovations, which go beyond our current imagination. Inspired by the above, this dissertation thesis discusses key elements which have been recently introduced as the potential 5G enablers. As each of previously mentioned mobile generations has been driven by new application use-cases and the associated users' demands, we assume the same also for upcoming 5G networks. Due to that, this dissertation work is, as well, giving an insight into end user's perception of newly arriving technological changes and applications which is an essential performance indicator of overall adoption of 5G. One of the most rapidly developing applications, where the 5G is expected to fulfill its needs, is Internet of Things (IoT). Moreover, researchers are exploring new applications in directions of augmented reality (AR) and virtual reality (VR), Internet of Vehicles (IoV), Tactile Internet (TI), Device-to-Device (D2D) communications, Machine-to-Machine (M2M) communications, named also Machine-Type Communications (MTC) [5].

Due to that, this dissertation work is as well giving an insight into end user's perception of newly arriving technological changes and applications which is a performance indicator of overall adoption of 5G principles. One of the most rapidly developing applications, where the 5G is expected to fulfill its needs is Internet of Things (IoT); nowadays often called as the Internet of Everything (IoE) – a concept that extends the IoT emphasis on M2M communications to describe a more complex system that also encompasses people and processes [6]. Projected massive number of sensors and daily-life devices mutually interacting and sharing data without any human interaction is seeking for a new communication platform which will be capable to handle all associated issues [7].

Since it is already clear that not all these challenges can be accommodated even by current wireless networks, the next-generation (5G) networks should take this role and act as an enabler for upcoming communication use-cases – the 5G related activities in Europe are discussed in Table A.1. It is more than evident that 5G is a very broad research topic with many technical, social and business aspects [5], [7], [8]. Therefore, it is not an objective of present dissertation thesis "*Heterogeneous Connectivity of Mobile Devices in 5G Wireless Systems*" to cover all of them, but rather explore in more detail selected domains mentioned in Section 1.3.

1.2 State-of-the-art Issues of 5G Wireless Systems

Over the last few years, it was not even clear what the “5G” really stands for and what kind of technologies, communication protocols and applications will be the biggest drivers of this new cellular infrastructure. As the technology pillars in the architecture of future 5G mobile networks were identified, a diversity of wireless technologies will collaborate to support the 5G communication networks with their demanding applications and services. Despite decisive progress in many enabling solutions, next-generation cellular deployments may still suffer from a glaring lack of bandwidth due to inefficient utilization of radio spectrum, which calls for immediate action.

As technical envelope of 5G vision, there are several broadly discussed performance criteria which are expected to be delivered by fifth-generation (5G) systems. In this dissertation thesis, the most important of them are covered:

- Virtually unlimited capacity and ubiquitous coverage introducing the “anytime & anywhere” connectivity. Serious increase of network throughput ($1-10$ Gbps).
- High degree of flexibility & network intelligence of all involved technology components to deliver most of the services “on-demand” – with respect to meet agreed Quality of Service (QoS) and Quality of Experience (QoE).
- Significantly lower end-to-end latency (below 1 ms) to enable new application scenarios e.g., Tactile Internet (TI).
- Unrestricted mobility to enable the mobile broadband even for very fast moving objects (up to 500 km/h) e.g., controlled dynamic spectrum sharing at the airport.
- Energy efficient communication to reduce power consumption at the side of end users and telecommunication operators.

Despite very active research during last couple years resulting in a variety of promising solutions created across academia and industry as well, the true 5G landscape is still not there yet. However, main essential is already known - all technical and user requirements can be barely fulfilled by a single Radio Access Technology (RAT). Therefore, as fundamentally different to previous generations of cellular systems, the 5G networks will not be just an incremental advance of 4G, but rather constructed as a set of directly bounded communication technologies and protocols [9].

While in recent cellular systems, the selected wireless technologies have been developing and operating individually, the 5G needs significant increase in network capacity and throughput. Therefore, it requires a tighter interconnection and cooperation between different types of RATs. As a result, it becomes unavoidable to aggregate different radio technologies as part of a common converged radio network – to be transparent to the end users, and develop techniques that can efficiently utilize the radio resources available across different spectral bands [10]. Following this vision, the Heterogeneous Networks (HetNets) represent a key building block of next-generation 5G systems, where different RATs operating in licensed (LTE) as well as unlicensed spectrum (WiFi) are collectively providing the multiplied performance [11], [12].

With respect to the convergence of various RATs, the telecommunication operators increase the density of their mobile networks by deploying new cells with different coverage – to boost the overall network capacity [13] – since the multi-RAT concept together with continuing network densification are still not providing satisfactory outputs (from 5G perspective), especially due to limited space and narrow frequency bandwidth of all legacy wireless technologies.

Therefore, the heterogeneous deployments (infrastructures) have to be provided by novel wireless communication technologies – utilizing extremely high frequency millimeter-wave (mmWave) band ranging from 3 to 300 GHz [14]. Of course, the mentioned mmWave communications are naturally not suitable for long-range use-cases since the wave length can not infiltrate from dense materials efficiently. Therefore, it can be easily dispersed by rain drops, gases, and flora. Nevertheless, mmWave and Visible Light Communication (VLC) technologies can improve the transmission data rates for indoor setups, because they have come up with large bandwidth. This, in fact, particularly supports one of the key ideas of designing the 5G cellular architecture – the outdoor and indoor scenarios should be physically separated, so that penetration loss through building walls can be limited or even fully avoided [15].

1.3 Scope of the Dissertation Thesis

This dissertation thesis targets various aspects of wireless communications with respect to the heterogeneous connectivity of mobile devices in fifth-generation (5G) wireless systems. In particular, three key research domains are comprehensively studied:

1. **Mobile Networks in the 5G era** – the 5G wireless systems include an extreme diversity of available connectivity solutions, which need first to be harmonized across multiple application use-cases, and then properly orchestrated in order to meet the 5G technical Key Performance Indicators (KPIs).
2. **Proximity-based (cellular-assisted) networking / data offloading mechanisms** – mobile network operators are struggling to handle the rapidly increasing amounts of data traffic on their networks. As a result, the 3rd Generation Partnership Project (3GPP) is currently investigating possible scenarios for Device-to-Device (D2D) data offloading in LTE networks. However, it remains unclear what kinds of gains can be expected from in-band D2D solutions. By comparison, the already available WiFi Direct D2D technology enables offloading onto unlicensed bands at data rates generally higher than infrastructure cellular links.
3. **Power control mechanisms and dynamic allocation of spectrum resources in 4G+ cellular networks** – the new generation cellular networks need to increase their capacity to support the large amount of traffic generated by diverse users. The telecommunication operators are deploying heterogeneous networks, with base stations covering very small areas in locations with high bandwidth demand to address growing clients' needs. The femto cells and small cells are often installed indoors, to serve the clients of a single building, such as a shopping mall or an office building – the indoor environment is characterized by high variability in signal level, caused by large number of walls and other obstacles attenuating and reflecting the radio signal. To be able to correctly scale the network towards the clients' requirements, the telecommunication operators must predict and estimate the network throughput. The fifth-generation wireless systems aim to decisively advance on the (i) levels of spectral and energy efficiency, (ii) user experienced throughput, as well as (iii) communication latency, and (iv) reliability. They prepare to rely on leveraging extremely high frequency (i.e., mmWave) spectrum bands, employing massive Multiple-Input Multiple-Output (MIMO) techniques, as well as deploying increased numbers of small cells with various sizes and across different frequencies. However, the use of mmWave radios is costly and the key enabling technology is still under standardization, whereas massive MIMO requires complex and expensive coordination that is difficult to achieve in practice. Therefore, the main feasible method to offer larger capacity on existing pre-5G deployments is via extreme network densification.

1.4 Thesis Outline and Main Results

This dissertation thesis consists of three main chapters which cover author's research activities over the years 2013 – 2017. Provided results represent the most significant author's outcomes published in well-recognized scientific journals or proceedings of the international conferences and workshops.

As the dissertation thesis contains three key chapters (2, 3, 4), each chapter consists of: (i) state of the art, (ii) problem formulation, (iii) proposed solution, (iv) implementation, and (v) results evaluation. All together, mentioned chapters represent the author's research angles comprehensively investigating the "*Heterogeneous Connectivity of Mobile Devices in 5G Wireless Systems*" and form a coherent output of this dissertation thesis. Having at his disposal the possibility to access the experimental LTE deployment at Brno University of Technology (BUT), Czech Republic, which supports most of the functionality expected of the LTE Release 10 communication system, author was able to conduct (design, implement and evaluate) the key parts of his present research with the support of this real cellular system. As this stands for the important point of this Ph.D. work, the particular configurations of the experimental network for all designed mechanisms are described in detail in Chapter 3 and Chapter 4.

After the Introduction 1, in which the core motivation and scope of this research work are highlighted, three main chapters follow. The Chapter 2 provides insights into the technical challenges (together with requirements and standards) and emerging technologies broadly presented as 5G vision's enablers. Further, in Chapter 3, the proximity-based D2D communication utilizing the network-assisted data offloading of LTE traffic onto WiFi Direct (WFD) is thoroughly discussed. The resulting real-world measurements from this chapter quantify the numerical effects of D2D functionality on the resultant system performance. Consequently, they shed light on the general applicability of LTE-assisted WFD solutions and associated operational ranges. In addition, Chapter 3 ends with the discussion of new challenges in constructing meaningful proximity-based services with high levels of user adoption. They call for a comprehensive investigation of user sociality and trust factors jointly with the appropriate technology enablers for secure and trusted D2D communications, especially in the situations, where cellular control is not available or reliable at all times.

Chapter 4 evaluates in its first third the interference mitigation techniques based on the transmit power management in indoor LTE deployment. Inspired by the fact that the need for greater indoor coverage and capacity becomes more urgent as the ubiquitous connection to the Internet is required from the end users, a comprehensive summary on live trial of transmission power optimization within the full-featured 3GPP LTE-A indoor deployment is provided. To deliver a thorough view on the configuration of transmit power, an evaluation between results provided by developed PyLTEs software and optimized configuration of TX power scheme is given. Further, in the rest of Chapter 4, the concept of the Licensed Shared Access (LSA) regulatory framework enabling spectrum sharing is described. This powerful concept has been subject to several early technology demonstrations that confirm its implementation feasibility. Nevertheless, the full potential of LSA-based spectrum management can only become available if it is empowered to operate dynamically and at high space-time-frequency granularity. The functionality that is required by the LSA system to achieve the much needed flexible operation is discussed within the scope of the Chapter 4. Further, the report on the results of our respective live trial that employs a full-fledged commercial-grade cellular network deployment is outlined at the end of this chapter. The last, but not least, Chapter 5 concludes the research work and discusses the key outcomes.

2 MOBILE NETWORKS IN 5G ERA

It has been more than a few decades since mobile wireless communications were introduced with the first generation, voice-only mobile systems. Going further, over the last couple of decades, the society has witnessed gradual, yet steady evolution of mobile wireless communications towards second, third and fourth generation wireless networks. Introduction of digital modulations, effective reuse of frequencies, penetration of packet-based Internet communications and rapid advancement in physical layer technologies e.g., Wideband Code Division Multiple Access (WCDMA), Orthogonal Frequency-Division Multiple Access (OFDMA), MIMO, and Hybrid Automatic Repeat Request (HARQ) have played a significant role towards this gradual evolution [1], [16]. The comprehensive comparison of evolution of the wireless technologies is outlined in Table A.2.

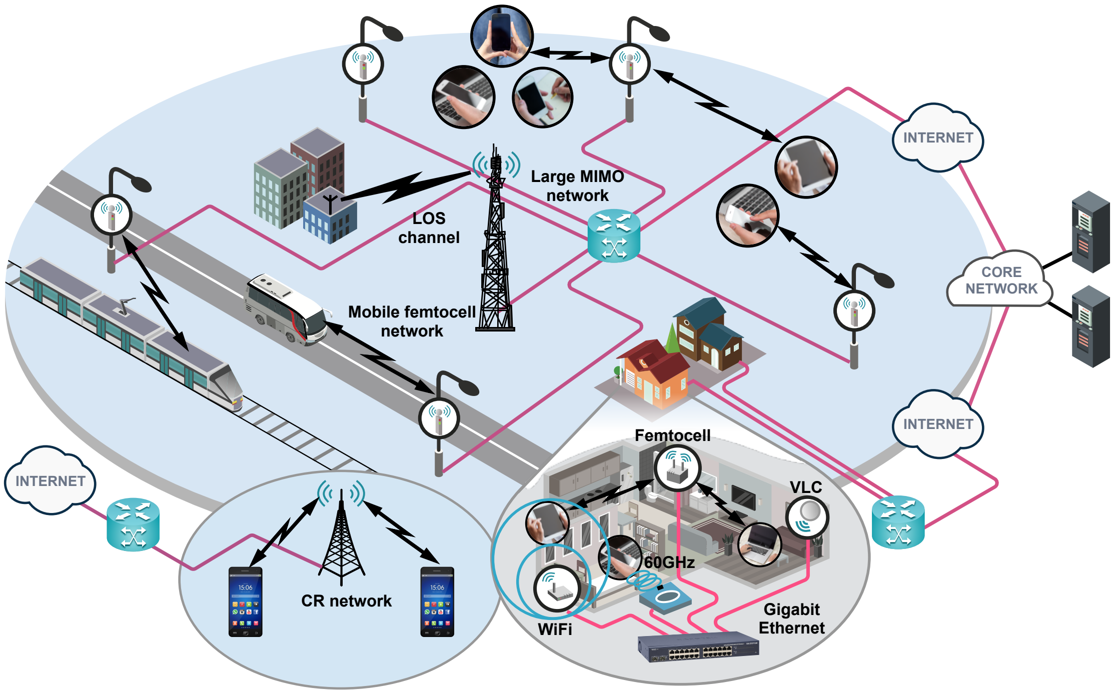


Fig. 2.1: Considered 5G heterogeneous wireless cellular architecture.

On top of this, with the ever increasing popularity of smart devices, currently all-IP based fourth generation (LTE) mobile networks have become a part of everyday life – providing a set of new, user-oriented mobile multimedia applications (e.g., mobile video conferencing, streaming video, and online gaming). These new applications are not only satisfying users' requirements (QoS, QoE), but also opening up new business horizons for telecommunication operators to increase their revenue, see Fig. 2.1 [8].

2.1 Existing Cellular Networks – Issues and Challenges

A quick look into recent wireless network statistics reveal that global mobile traffic grew 63 % in 2016 and almost half a billion (429 million) mobile devices and connections were added in 2016 [4]. Globally, smart devices represented 46 % of the total mobile devices and connections in 2016; they accounted for 89 % of the mobile data traffic. Another interesting finding is that smartphones represented only 45 % of total mobile devices and connections in 2016, but represented 81 % of total mobile traffic. Cisco's Visual Networking Index (VNI) forecasts that by 2021, nearly three-quarters of all devices connected to the mobile network will be "smart". In fact, since 2012 video traffic is more than half of the global mobile traffic [4]. An average mobile user is expected to download around 1 terabyte of data annually by 2020 [17]. Moreover, researchers are exploring new application use-cases in directions of Augmented / Virtual Reality (AR / VR), Internet of Things, Internet of Vehicles, Device-to-Device communications and Machine-to-Machine communications [1], [2], [5].

Indeed, different research studies have been launched over the last years to understand, how cellular systems need to evolve to be able to provide efficient access to M2M / IoT networks. It is important to highlight that M2M principles are fundamentally different from humand-based (Human-to-Human; (H2H)) communications. These differences require a mentality shift on the way that cellular systems have been designed. A summary of the main differences between M2M and H2H traffic is shown in Table 2.1 [18], [19].

Based on the above, supporting this enormous and rapid increase of data usage and connectivity is an challenging task in present 4G (LTE) cellular systems. Furthermore, while currently deployed LTE networks were originally designed to support up to 600 Radio Resource Control (RRC)-connected users per cell [21], M2M communications and IoT requires supporting of tens of thousands of connected (smart) devices within a single cell. Therefore, LTE cellular network is exploring avenues of different research and development e.g., MIMO, HetNets, data offloading techniques and dynamic spectrum sharing to enhance network capacity and data rates [17].

2.2 Emerging 5G Use Cases and Applications

A wide variety of new emerging 5G applications put pressure on the commercial roll out of 5G wireless systems. 5G network architecture is expected to provide network solutions for a wide range of public and private sectors i.e., energy, agriculture, city management, health

Tab. 2.1: Differences between human-based and M2M communications [18], [19], [20]

	Human-based	Machine-to-Machine
Traffic Direction	Mostly downlink; although uplink traffic is increasing over the last years due to interactive applications such as social networking, humans still download more than they upload.	Mainly uplink data to report sensed information. For some applications, symmetric uplink and downlink capacity is needed in order to allow for the dynamic interaction between sensors and actuators.
Message Size	The size of the messages is generally big, motivated by demanding applications such as multimedia and real-time transmissions, including video streaming.	The size of the messages is generally very short (e.g.very few bits of the reading of a meter, or even just 1 bit to inform of the existence or absence of a given event).
Connection and Access Delay	Human-based applications tend to be very demanding once a connection has been established. However, although not desirable, longer connection delays are typically well tolerated.	Many M2M applications will be based on duty-cycling, i.e., having devices sleeping and just waking up from time to time to transmit data. For some applications, the connection delays should be very short to ensure quick access to the network when waken up.
Transmission Periodicity	Human-based data traffic is very random and asynchronous in nature. In addition, the frequent transmission of control information is required to ensure high throughput and good delay performance.	Very wide range of alternatives. For many applications, transmissions will be very sparse in time. In addition, many applications will have known periodic patterns (e.g., programmed tasks).
Mobility	Mobility management and exchange of location information are constantly required to ensure seamless connectivity and allow for roaming.	For most of M2M applications, mobility is not a major concern. Some applications may have no mobility at all.
Information Priority	In general, there is no major differentiation between users in terms of priority, but only between applications for each user.	Some M2M applications may transmit critical information and thus require very high priority with a detailed level of granularity.
Number of Devices	At most, hundreds of devices per connection point. Typically, tens of devices per connection point.	Higher than in human-based communications. Hundreds or thousands of devices per connection point.
Security and Monitoring	Humans can raise an alert in the case of troubleshooting or tampering.	M2M devices cannot raise an alert in the case of malfunctioning or tampering.
Lifetime and Energy Efficiency	Humans can recharge batteries in a daily manner.	Once an M2M network has been deployed, some devices may require to operate for years or decades without maintenance.

care, manufacturing and transport, with significantly improved user experience [22]. Aside from the enormous number of connections, 5G networks also have to support diverse nature of devices and their associated service requirements; the minimum technical performance requirements of 5G wireless systems given by IMT 2020 are detailed in Table 2.2 [23].

Although research and development in some of these applications are already underway in 4G wireless, original 4G LTE standards, 3GPP LTE Release 8 [24] did not include support to any of these applications. Rather, these applications were spawned later, and started explosive increase in wireless data usage, thereby imposing additional utilization of resource constrained 4G wireless networks. Naturally, later releases of 4G LTE networks, often named as "LTE Advanced", gradually started to include these applications. On the other hand, it is expected that massive bandwidth of 5G mmWave communications will provide a native support for these emerging applications. In this section, some of the demanding applications i.e., D2D communications, M2M communications, IoV, IoT and healthcare are discussed in detail. Emerging 5G applications in beyond 4G wireless systems are further summarized in Table 2.4.

2.2.1 D2D Communication

Device-centric nature of the emerging 5G applications is expected to enable the smart-device in proximity to transmit data directly without the need to communicate with the Base Station (BS) for sharing the relevant content [7]. As the thorough literature review of D2D communication is given in [25], in this section, the major research activities in this field related to the context of the emerging 5G wireless communications are discussed. Major recent directions in D2D include game theoretic pricing schemes [26], social networking prototypes [27], [28], secure network-assisted D2D communication [29], [30], public safety networks [25] and maximum acceptable distance estimation for commercial roll out [31]. The smart home, which is considered to be one of the communication scenario for D2D, is shown in Fig. 2.2.

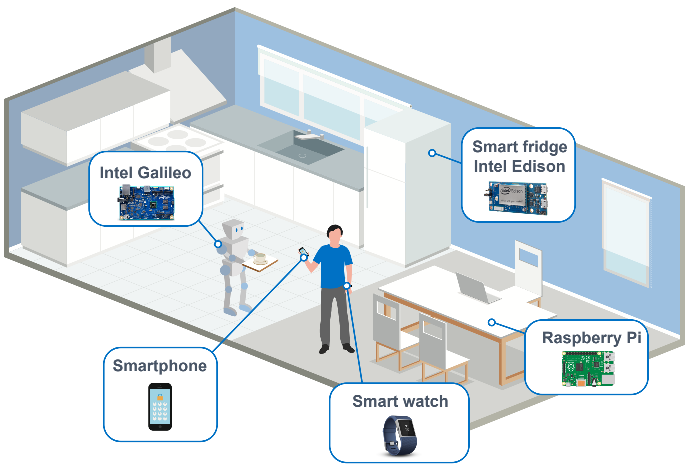


Fig. 2.2: Future secure smart home "D2D" environment [28].

Further, an ad-hoc D2D wireless network composed of 5G wireless devices (devices utilizing various kind of communication technologies), using the group key agreement and routing process is proposed in [32]. Low latency, energy efficiency and communication scalability are fundamental for upcoming 5G networks. Following this fact, it is essential to decrease the control signaling and end-to-end latency in network assisted D2D communications [33], [34][1]. Proposed system level improvements can therefore support a reliable Vehicle-to-Vehicle (V2V) transmissions in 5G networks. Spectrum sharing, interference management, multi-hop communication and energy efficiency are logically the major challenges in dense 5G mobile environment and represent the key part of this ecosystem [35], [36].

2.2.2 M2M Communication

Comparable to D2D communications, M2M communications are also expected to play crucial role with their native support in 5G wireless systems [7]. Based on the information given in [25], [38], [39], [40], M2M communication can be described as "Data communication among machines or devices that does not require human mediation nor impose specific restrictions on communication ranges". The communication between machines is routed through the core networks via base stations and remote servers, even if source and destination are proximate to one another. In comparison, D2D communication presumes a distance limit between devices and relies only on local device capabilities without centralized infrastructure support. Moreover, M2M is application-oriented and technology-independent approach, whereas D2D is technology-dependent and focuses on proximity services, which assumes opportunistic connectivity [25], [38], [39]. The main application of M2M is to automatically collect and deliver measurement information. D2D communication, as a new communication pattern, can be used for M2M communication to improve network performance and reduce transmission delay [38], [39].

Major features of M2M communications comprise of automated data generation, processing, transfer and data exchange between smart devices (machines), and infrequent data transmission, with minimum human interaction, see Fig. 2.3 [41].

M2M communications envision: (i) considerable number of devices with small amount of data, (ii) sporadic transmissions, (iii) high reliability, (iv) low latency, and (v) real-time operation. Major reviews of published M2M research works contain various commercial, hardware and proof-of-concept frameworks [43] as well as major architectural improvements, network functionalities and research challenges [44]. Latest advances and development directions in architecture, communication protocols, standards and security for M2M evolution from 4G to 5G are outlined in [45]. Network unpredictability and mobility often lead to complex interference within M2M devices, as well as between M2M networks and cellular networks [46]. Therefore, it is expected that Cognitive Radio (CR) or other

[1] Nokia Research Center introduced smart mobility management, D2D-aware handover and D2D triggered handover solutions [33].

Tab. 2.2: Minimum technical performance requirements for the 5G wireless systems of IMT 2020 [2], [23], [37], [3]

KPI	Key Use Case	Values
Peak Data Rate	eMBB	DL: 20 Gbps, UL: 10 Gbps
Peak Spectral Efficiency	eMBB	DL: 30 bps/Hz, UL: 15bps/Hz
User Experienced Data Rate	eMBB	DL: 100 Mbps, UL: 50 Mbps (Dense Urban)
5% User Spectral Efficiency	eMBB	DL: 0.3 bps/Hz, UL: 0.21 bps/Hz (Indoor Hotspot); DL: 0.225 bps/Hz, UL: 0.15 bps/Hz (Dense Urban); DL: 0.12 bps/Hz, UL: 0.045 bps/Hz (Rural)
Average Spectral Efficiency	eMBB	DL: 9 bps/Hz/TRxP, UL: 6.75 bps/Hz/TRxP (Indoor Hotspot); DL: 7.8 bps/Hz/TRxP, UL: 5.4 bps/Hz/TRxP (Dense Urban); DL: 3.3 bps/Hz/TRxP, UL: 1.6 bps/Hz/TRxP (Rural)
Area Traffic Capacity	eMBB	DL: 10 Mbps/m^2 (Indoor Hotspot)
User Plane Latency	eMBB, URLLC	4 ms for eMBB; 1 ms for URLLC
Control Plane Latency	eMBB, URLLC	20 ms for eMBB; 20 ms for URLLC
Connection Density	mMTC	1 000 000 devices/km^2
Energy Efficiency	eMBB	Capability to support high sleep ratio and long sleep duration to enable low energy consumption when there is no data
Reliability	URLLC	$1-10\text{m}^{-5}$ success probability of transmitting a layer 2 protocol data unit of 32 bytes within 1 ms in channel quality of coveradge edge
Mobility	eMBB	Up to 500 km/h
Mobility Interruption Time	eMBB, URLLC	0 ms
Bandwidth	eMBB	At latest 100 MHz; Up to 1 GHz for operation in higher frequency bands (e.g., above 6 GHz)
Note: enhanced Mobile Broadband (eMBB); massive Machine Type Communications (mMTC); Ultra-Reliable and Low Latency Communications (URLLC).		

approach e.g., Licensed Shared Access (LSA) will emerge and assist in developing novel cognitive M2M architecture for sensing and using the available frequency bands [41], [47].

MTC Support in Cellular Systems

Considering the demanding requirements of M2M communications [48], even the previous generation of mobile networks can be taken into account for some communication use-cases. The 2G mobile systems, which was the first generation ready to use for data transmissions, (i.e., Global System for Mobile Communications (GSM) and General Packet Radio Ser-

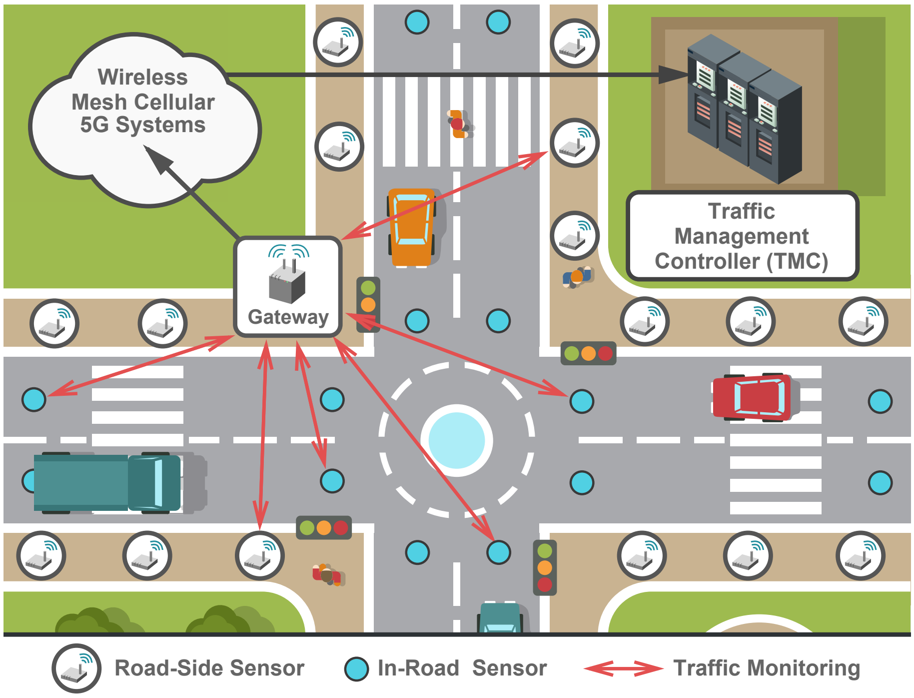


Fig. 2.3: Smart transportation deployment of M2M devices (sensors) within the 5G-Grade communication infrastructure [42].

vice (GPRS) / Enhanced Data rates for GSM Evolution (EDGE)) provide: (i) optimized power consumption and low costs (i.e., CAPEX and OPEX), (ii) global coverage, and (iii) existing communication infrastructure. However, from the long-term perspective and economic point of view, utilized frequency bands have to be revised for the next-generation (5G) systems [49]. On the contrary, the 3G mobile networks (i.e., UMTS and High Speed Packet Access (HSPA)) have a lower power efficiency and higher radio module (modem) cost than the 2G mobile systems. The potential of 3G exceed the given requirements of many low-end IoT application use-cases and may therefore be a less preferable technology for upcoming IoT / M2M applications[2].

Currently deployed 4G technologies, i.e., LTE and LTE-A, are interesting since their capabilities are in line with the requirements for very demanding Machine-Type Communication (MTC) applications; the radio interface and OFDMA allow the scaling of the system bandwidth according to needs. Modem cost in early LTE releases is however an issue and the coverage is in some markets still irregular – even if coverage increases quickly on a global level [50]. A valid argument for use of 4G LTE for MTC applications is to benefit from improved spectral efficiency and the bandwidth flexibility offered by 4G systems and longevity of the technology as a future cellular system. Although the 4G coverage can be even today non-uniform, the situation is getting better and the challenge of adapting 4G LTE mobile systems, that were specifically designed for efficient broadband communications, can be met already on these days [51].

[2]On the other hand, the 3G has however proven in the past to be popular for e.g., automotive M2M applications and other more demanding M2M applications due to the wide range of data rates required.

Based on above text, 5G may thus be a timely communication technology offering lower cost, lower energy consumption and support for very large number of smart devices. Indeed, mentioned requirements are at the forefront of the 5G MTCG design and – if successful – without any doubts, it will be a key part of the Internet of Things in the coming years.

2.2.3 Internet of Things

Looking back, first patterns of IoT connectivity can be dated back to the 1980s, with the legacy Radio Frequency Identification (RFID) technologies, and back to the 1990s, with the Wireless Sensor Networks (WSNs). Due to their promising application scenarios, they gained a lot of attention both in business and consumer market. Therefore, going further, for the first decade of the 21st century, industrial alliances invested a lot of effort in developing standardized low power IoT solutions [8].

The first solutions available on the market were proprietary-based, such as WirelessHART and Z-Wave. Those solutions have actually delayed the initial take off of the IoT, due to interoperability issues, among different vendors. Based on this experience, more generic communication technologies have been developed by industrial alliances and working groups i.e., Institute of Electrical and Electronics Engineers (IEEE), European Telecommunications Standards Institute (ETSI), 3rd Generation Partnership Project (3GPP), and Internet Engineering Task Force (IETF), providing the interconnection and Internet-connection of constrained devices – Bluetooth, and the IEEE 802.15.4 standard have played an important role in the IoT evolution since they were on the market right on time. Recently, the IEEE 802.15.4 Physical (PHY) and Medium Access Control (MAC) layer have been complemented by an IP-enabled IETF protocol stack. The IETF 6LoWPAN [52] and IETF ROLL [53] working groups have played a key role in facilitating the integration of low-power wireless networks into the Internet, by proposing mainly distributed solutions for address assignment and routing. At the same time, the 3GPP has been working towards supporting M2M applications on 4G broadband mobile networks, such as Universal Mobile Telecommunication System (UMTS) and LTE, with the final aim of embedding M2M and MTCG communications within the 5G systems [54].

None of the aforementioned technologies has emerged as a market leader, mainly because of technology shortcoming and business model uncertainties. Now, the IoT connectivity field is at a turning point with many promising radio technologies emerging as true M2M connectivity contenders:(i) Low-Power WiFi, (ii) Low-Power Wide Area (LPWAN) networks, (iii) Narrow-Band NB-IoT, (iv) LTE-M, and (v) several improvements for cellular M2M systems [54]. These solutions are therefore very attractive for IoT deployments, being able to fulfill availability and reliability requirements, see Table 2.3 (in this comparison, the NB-IoT and LTE-M are evaluated following the available information at the time of writing this dissertation thesis; therefore, the situation may change once the real implementations (not only technical specifications) become a reality).

Tab. 2.3: IoT KPIs covered by modern communication technologies

	ZigBee	**BLE**	**LP-WiFi**	**LPWAN**	**3GPP Rel.8, Rel.10**	**NB-IoT, LTE-M**
Scalability	✗	✗	✓	✗	✓	✓
Reliability	✗	✓	✓	✗	✓	✓
Low Power	✓	✓	✓	✓	✗	✓
Low Latency	✗	✓	✓	✗	✓	✓
Large Coverage	✗	✗	✓	✓	✓	✓
Low Module Cost	✓	✓	✓	✓	✗	✓
Mobility Support	✗	✗	✗	✓	✓	✓
Roaming Support	✗	✗	✗	✓	✓	✓
SLA Support	✗	✗	✗	✗	✓	✓

Tactile Internet

After creating the mobile Internet, connecting billions of smart devices (smart phones and laptops), the focus of mobile communications is moving towards providing ubiquitous connectivity for machines and devices, thereby creating the Internet of Things paradigm [55]. With the technological advancements of today, the communication stage is ready for the emergence of the Tactile Internet (TI) in which the ultra-reliable and ultra-responsive network connectivity will enable to deliver requested real-time control and physical tactile experiences remotely. The Tactile Internet will therefore provide a true communication paradigm shift from content-delivery to skill-set delivery networks, and thereby reform almost every segment of the society. Following the information given by International Telecommunication Union (ITU), the Tactile Internet will add a new dimension of human-to-machine interaction by delivering low latency (communication delay) to setup real-time interactive communication systems. Further, the TI has been described as: a communication infrastructure linking together (i) lower latency (< 1 ms), (ii) very short transition time, (iii) high service availability, and (iv) high level of security [56], [57]. Associated with cloud computing proximity through e.g., mobile edge-clouds and combined with the virtual or augmented reality for sensors and haptic controls, the Tactile Internet addresses areas with reaction times in order of a millisecond e.g., real-time gaming, transportation systems, health and education.

Because the Tactile Internet will be servicing the mession critical use-cases of society (e.g., automation in industry, autonomous driving, robotics, healthcare, virtual and augmented reality), it will need to be ultra-reliable, with a maximum outage of a second per year [58], support very low latencies, and serve sufficient capacity to communicate with each other simultaneously and autonomously. Following mentioned facts, the proposed architecture will be able to interconnect TI with traditional representatives like wired Internet, the mobile Internet, and the IoT – forming an Internet of absolutely new dimen-

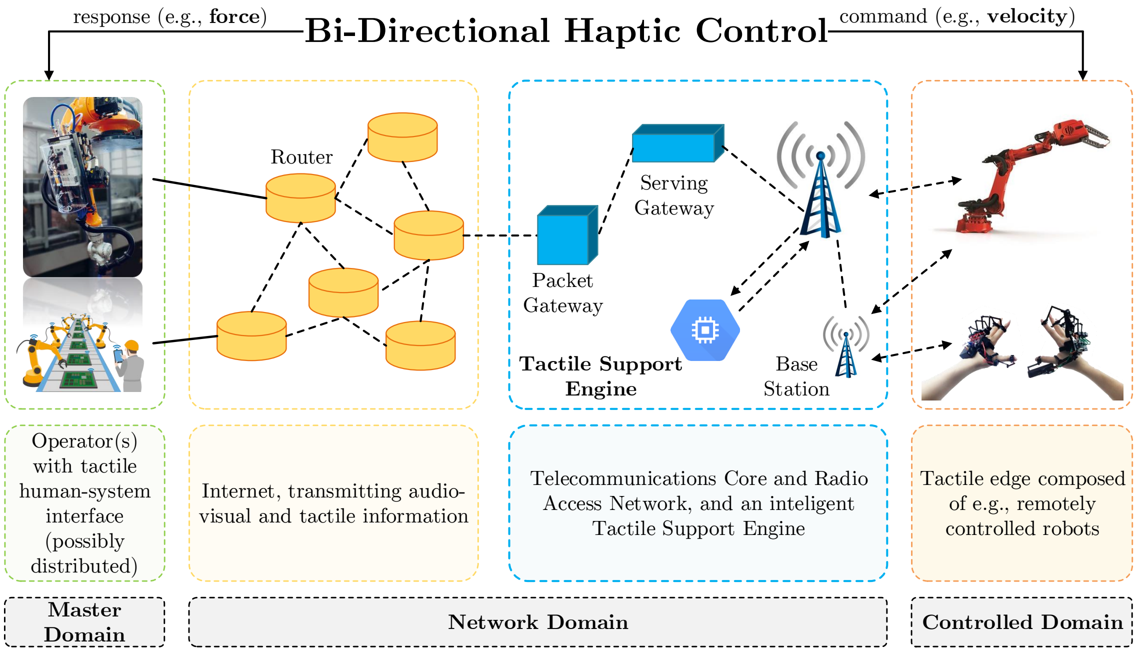


Fig. 2.4: Functional representation of the Tactile Internet architecture [58].

sions and capabilities. Since the state-of-the-art fourth generation (4G) mobile systems do not fulfill the given technical requirements for the TI, the fifth generation (5G) mobile communications systems are expected to underpin the TI at the wireless edge.

Health Care and Wearables

Advancements in sensing and communication technology have opened up new possibilities for health monitoring [59]. Wearable technologies promises to provide health care solutions to growing world strained by the aging population [60]. Devices with capabilities of measuring multiple signals in ambulance are being developed these days [61]. The record of multiple physiological signals over a long time period helps in understanding the disease pathophysiology [61]. Improved addressing, extended security services and higher bandwidth enables new possibilities of healthcare [62]. Emerging 5G wireless and Body Area Network (BAN) are facilitating a paradigm shift in real-time remote patients' health monitoring.

The major constraint in real-time data collection and monitoring is bandwidth limitation. Higher bandwidth and data rates of 5G wireless [62] are expected to resolve this bandwidth constraints. Comfort, physical, psychological and social aspects of wearable devices are discussed in [63]. These capabilities require huge data processing, storage and real time communications. An IoT based system, utilizing with big data and cloud computing concepts, for emergency medical services is presented in [63]. Due to the above mentioned facts, 5G wireless architecture is expected to resolve big data challenges of real-time health care applications bringing benefits to humanity [64].

2.2.4 Augmented and Virtual Reality

Leveraging recent advances in (i) storage / memory, communication / connectivity, (ii) computing, (iii) big data, (iv) artificial intelligence (AI), (v) machine vision, and (vi) other areas will enable the implementation of immersive communication technologies as augmented and virtual reality (AR, VR). These technologies will enable the transmission of ultra-high resolution video and sound in real time through the relay of its various sights, sounds, and emotions. The use of VR will go beyond early adopters such as gaming to enhancing cyber-physical and social experiences such as conversing with family and acquaintances, business meetings, and disabled persons. Add to this the growing number of drones, robots, and other self-driving vehicles taking cameras to places humans could never imagine reaching; we shall see a rapid increase of new content from fascinating points of view around the world. Ultimately, VR will provide the most personal experience with the closest screen, providing the most connected, most immersive experience [65].

Augmented reality and virtual reality represent two ends of the communication spectrum. On the one hand, AR is based on reality as the main focus, and the virtual information is presented over the reality. On the other hand, VR is based on virtual data as the main focus, immersing the user into the middle of the simulated reality virtual environment. One can also imagine a mixed reality where AR works together with the VR, by merging the physical and virtual information seamlessly, see Fig. 2.5 [66].

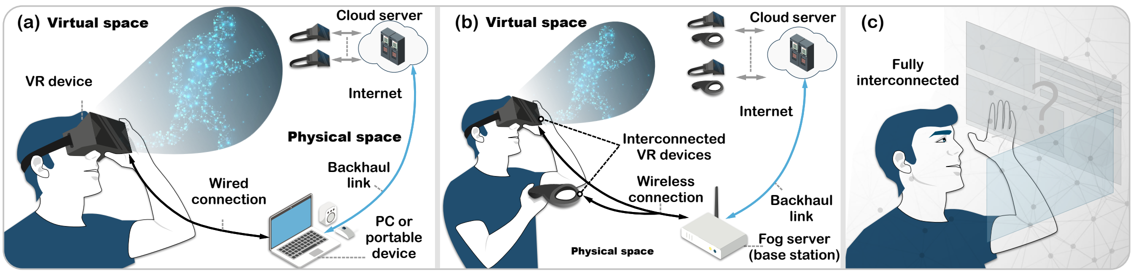


Fig. 2.5: Illustration of virtual reality scenarios: a) current virtual reality systems; b) interconnected systems; c) fully interconnected.

Current online social networking sites i.e., Facebook, Twitter are just precursors of what we will come when social networking encompasses immersive VR technology. At its foundation, social VR allows two geographically separated people to communicate as if they were face to face. They can make eye contact and can manipulate virtual objects that they both can see. Current VR technology is in its inception since headsets are not yet able to track exactly, where eyes are pointed, by instead looking at the person to whom one is talking. Moreover, current state-of-the-art VR technology is unable to read detailed facial expressions and senses. Finally and perhaps most importantly, most powerful VR prototypes are wired with cables because the amount of transmitted high-resolution video at high frame rates simply cannot be done using today's wireless technology (4G / LTE), let alone the fact that a perfect user interface is still in progress. These shortcomings have started efforts to make social VR happen in the near future [66], [67].

2.2.5 Complementary Applications

Aside the above-mentioned applications in 5G wireless systems, the financial industry, with increasing businesses and customers, also requires strong computing and data processing. Application of grid computing in financial industry is discussed in [68]. Therefore, 5G based future mobile networks have a huge potential to transform different financial services [69] e.g., banking, payments, personal finance management, peer to peer transaction and local commerce.

Tab. 2.4: Emerging "killer" applications of 5G wireless systems

Area	Related Works	Key Points
D2D Communications	[7], [25], [26], [27], [32], [31], [33], [35], [36], [74]	• Peer-to-Peer data communication • Interference challenges • Group key agreement
M2M Communications	[7], [25], [26], [27], [32], [31], [33], [35], [36], [74]	• Massive number of devices • Automated data generation and processing • Relay stations • Converged mobile networks • Energy efficiency and cognitive M2M
Internet of Things	[64], [75], [76], [77], [78], [79], [80], [81], [82]	• Millions of parallel connections • Cloud integrated with diverse devices • Software defined IoT • Agent based architecture • Interoperability of hubs • Social IoT
Advanced Vehicular Communications	[83], [84], [85], [86], [87] [88], [89], [90], [91], [92], [93]	• Vehicular cloud • Autonomous vehicles • Big data • Social IoV • Intelligent IoV managements systems • Architecture: RAT for HST • Low latency / safety / QoS / QoE
Health Care and Wearable	[59], [60], [61], [62], [63], [64]	• Health monitoring • Multiple physiological signals • IoT/cloud for healthcare
Miscellaneous Applications	[68], [69], [70], [71], [72], [73], [94]	• Smart grids • Smart homes • Smart cities • Financial technologies

Sensing, communication and control increases efficiency and reliability of power grids, thereby modernizing them to Smart Grids (SGs). SGs use wireless networks for energy data collection, power line monitoring, protection and demand/response management [70]. Comparisons between smart and existing power grids are detailed in [71]. Smart information and smart communication subsystem are integral to smart grids [70], [71]. Smart grids seamlessly link physical components and wireless communications representing large scale cyber-physical systems [70]. Wireless technology is already being explored for efficient real time Demand-Response (DR) management [72]. High bandwidth and low latency of proposed 5G are expected to resolve many challenges associated with Smart Grids demand response.

Similarly, smart homes, with roots in automation, embedded systems, entertainment, appliances, efficiency and security is an active technical research area. Smart cities, with fundamentals of sustainability are gaining momentum. Major concepts of IoT, M2M, Cloud computing, integrated with 5G are very persuasive in these research areas [73]. The major related works in existing and future applications of 5G wireless systems are summarized in following Table 2.4.

2.3 5G Technology Enablers

In order to enable the ubiquitous connectivity required for many of the 5G-IoT applications, broad set of features and functionalities will need to be integrated to the currently predominantly broadband approach. This inherently leads us to a strong heterogeneous networking (HetNets) paradigm with multiple types of wireless access nodes (with different MAC/PHY, coverage, backhaul connectivity, QoS design parameters, etc.) [95], [96]. HetNets will offer the required seamless connectivity for the emerging IoT through a complex set of mechanisms for coordination and network management [97], [98]. Evolved 4G and emerging 5G networks will thus be characterized by interoperability and integration between various radio access networks, including those working with unlicensed frequencies. The aim of this section is to review recently finished 4G, currently ongoing 4G-Evolution as well as emerging 5G design efforts to provide an overall picture towards accommodating a heterogeneous networking [7]. The key differentiators (enablers) for the emerging 5G wireless systems from its 4G counterpart are detailed in Table A.3.

2.3.1 5G Radio Access Network Enablers

To provide a common connected platform for a variety of applications and requirements for 5G, the main technology components will be described on following lines within this section [5], [33], [66], [99].

Massive MIMO

Massive MIMO represents an evolving technology that has been upgraded from the current MIMO technology. The massive MIMO system uses arrays of few hundred antennas which are at the same moment in one time / frequency slot serving tens of user terminals. The main objective of this technology is to extract all the benefits of "classic" MIMO but on a significantly larger scale. In general, massive MIMO is an evolving technology of next-generation (5G) networks, which is energy efficient, robust, secure and spectrum efficient [100].

The massive MIMO depends on spatial multiplexing, which further relies on the base station – to have channel state information, both on the uplink as well as on the downlink. In case of downlink channel, it is not easy, but in case of uplink, it is feasible, as the end-terminals send pilot waveforms. On the basis of pilots, the channel response of each terminal is estimated. In conventional MIMO systems, the base station sends the pilot waveforms to the terminals and based on these, the terminal estimates the channel, quantizes it and sends feedback them to the base station.

This process is not implementable for massive MIMO systems, especially in high mobility conditions because of two reasons: (i) the downlink pilots from the base station must be orthogonal among the antennas, due to which the requirement of time, frequency slots for the downlink pilots increases with the increase in the number of antennas; (ii) as the number of base station antennas increases the number of the channel estimates also increases for each terminal which in turn needed hundred times more uplink slots to feedback the channel responses to the base station. A general solution to this problem is to work in Time Division Duplex (TDD) mode and depend on the reciprocity between the uplink and downlink channels [101].

Therefore, massive MIMO technology depends on phase coherent signals from all the antennas at the base station, but the computational processing of these signals is feasible to do within the 5G-ready infrastructure.

Millimeter Wave Technologies

As the demand for capacity in mobile broadband communications increases dramatically every year [4], wireless carriers must be prepared to support up to a thousand-fold increase in total mobile traffic by 2020. This situation encourages researchers to seek greater capacity and to find new wireless spectrum beyond the 4G standard. Recent studies suggest that mmWave frequencies could be used to augment the currently saturated 700 MHz to 2.6 GHz radio spectrum bands for wireless communications.

Today's microwave cellular systems, which are originally targeted to different application use-cases i.e., voice / data / video calling, have precious little spectrum: around 600 MHz are currently in use, divided among operators. Currently, there exist two ways to gain access to more microwave spectrum [102]:

- Repurpose or refarm radio spectrum – this option has occurred worldwide with the repurposing of terrestrial TV spectrum for applications such as rural broadband access. Unfortunately, refarming has not freed up that much spectrum, only about 80 MHz and at a high cost associated with moving the incumbents.
- To share spectrum utilizing e.g., cognitive radio techniques – the high hopes initially placed on cognitive radio have been dampened by the fact that an incumbent not fully willing to cooperate is a major obstacle to spectrum efficiency for secondary users.

Altogether, it appears that doubling the current cellular bandwidth is the best case scenario at microwave frequencies. Alternatively, there is an enormous amount of spectrum at mmWave frequencies ranging from 3 GHz to 300 GHz. Many bands therein seem promising, including most recently the local multipoint distribution service at 28–30 GHz, the license-free band at 60 GHz, and the E-band at 71–76 GHz, 81–86 GHz, and 92–95 GHz. Foreseeably, several tens of gigahertz could become available for 5G. Needless to say, work needs to be done on spectrum policy to render these bands available for mobile (cellular) communication. Signal propagation is not an insurmountable challenge. Recent measurements indicate similar general characteristics as at microwave frequencies, including distance-dependent path loss and the possibility of non-line-of-sight (NLOS) communication. A main difference between microwave and mmWave frequencies is the sensitivity to blockages – the information in [103], for instance, indicate a path loss exponent of two for line-of-sight (LOS) propagation but four (plus additional power loss) for non-line-of-sight. Therefore, mmWave cellular research will need to incorporate sensitivity to blockages and more complex channel models in the analysis, and also study the effects of enablers such as higher density infrastructure and relays. Another enabler is the separation between control and data planes.

Antenna arrays are a key feature in mmWave systems. Large arrays can be used to keep the antenna aperture constant, eliminating the frequency dependence of path loss relative to omnidirectional antennas (when utilized at one side of the link) and providing a net array gain to counter the larger thermal noise bandwidth (when utilized at both sides of the link). Adaptive arrays with narrow beams also reduce the impact of interference, meaning that mmWave systems could more often operate in noise-limited rather than interference-limited conditions. Since meaningful communication might only happen under sufficient array gain, new random access protocols are needed to work when transmitters can only emit in certain directions and receivers can only receive from certain directions. Adaptive array processing algorithms are required that can adapt quickly when beams are blocked by people or some device antennas become obscured by the user's own body [103].

Direct Communications

D2D communications represent a turning point in cellular systems. They entail the possibility that two devices can exchange data without the involvement of the BS or with just a partial aid from the base station [26]. As the basic principles of D2D communication were described in Section 2.2.1, this section deals with the description tightly connected with the offloading scenarios – future application use-cases within 5G systems. In contrast to WiFi / WiFi-Direct and Bluetooth technologies, which provide D2D capabilities in the unlicensed band, with D2D communications the QoS and QoE are controllable because of the use of the licensed spectrum. A new generation of scenarios and services in 5G wireless systems can hence be enabled, including: (i) device relaying, (ii) context-aware services, (iii) mobile cloud computing, (iv) offload strategies, and (v) disaster recovery. Based on above text, four different types of D2D communications can be distinguished [104]:

- Device relaying with telecommunication operator controlled link establishment – any device can broaden the coverage of the BS, by acting as a relay node.
- Direct D2D communication with operator controlled link establishment – any pair of network nodes can directly interact due to a D2D link, which is set up under the control of the telecommunication operator.
- Device relaying with device controlled link establishment – the endpoints of a data session are in charge of setting up a relaying infrastructure made of one or more relaying devices.
- Direct D2D communication with device controlled link establishment – any pair of devices can exchange messages thanks to a D2D link, which is established without any operator control.

Enabling D2D communication use-cases in the licensed band is essential to strengthening the support to mission critical applications and group communications. Besides these advantages of D2D communications, security, trust, interference management, resource discovery, and pricing issues should be addressed to capitalize the potential of this promising technology. These issues become very challenging when the D2D link is set up without any involvement of the base station. Moreover, new business models are required to answer the "pay for what" question. In fact, devices that act as relays will deplete their own resources (as battery, storage, communication, and processing) to assist the D2D model. Further, the cross-operator D2D capability is an open challenge complicated by the fact that frequency division duplex (FDD) spectrum bands are different for different telecommunication operators [26], [29], [104].

The RATs' principles (illustrated in first half of this section), will need to be supported by a suitable RAN technologies. Therefore, interesting propositions, which have been made with respect to the RAN, are discussed within the scope of remaining paragraphs of this section.

Decoupled Downlink/Uplink Channels

The traditional notion of a cellular cell is changing dramatically given the increasing degree of heterogeneity. Rather than belonging to a specific cell, a device would choose the most suitable connection from the many connections available. In such case, given that transmission powers differ significantly between downlink (DL) and uplink (UL), a wireless device that sees multiple BSs may access the infrastructure in a way that it receives the DL traffic from one BS and sends UL traffic through another BS. This concept had recently been introduced and is referred to as Downlink and Uplink Decoupling (DUDe) [105], [106], [107].

Licensed Assisted Access

Recently, the 3GPP commenced a work item on License Assisted Access (LAA), where licensed and unlicensed carriers are aggregated. LAA uses licensed frequency spectrum for control-related transmissions while sending data over both licensed and license-exempt carriers. Whilst mainly designed for high-capacity applications, the approach could be beneficial in the context of a ever-increasing amount of smart devices with increasing data rate demands. Notably, all non-critical IoT traffic could be transmitted via the license-exempt band whilst being controlled from the licensed band [108], [109].

Licensed Shared Access

In light of the above, it appears that the shared use of spectrum becomes unavoidable even for those who have conventionally enjoyed exclusive access rights [110]. However, the currently existing options of spectrum sharing (in primary licensed or unlicensed spectrum) do not offer much of the requested interference protection, therefore resulting in insufficient reliability, QoS guarantees, and predictability of operation. By contrast, the emerging Licensed Shared Access (LSA) regulatory concept allows for more advanced spectrum sharing between a limited number of entities with carefully defined usage rights, combining the benefits of command-and-control spectrum management with a flexible and innovative market-friendly approach.

Broadly, LSA approach (framework) enables authorized spectrum sharing by allowing at least two users, the incumbent (i.e., the current holder of spectrum rights) and the LSA licensee (i.e., the temporary user of spectrum) to access the same frequency bands in a licensed predetermined manner following a well defined mutual agreement [111]. In other words, LSA guarantees that the incumbent retains spectrum access rights anytime, anywhere, and the LSA licensee(s) will refrain from using this spectrum when needed by the incumbent (or at least will not disrupt the incumbent's operation).

Radio Access Network as a Service

The design of LSA management architectures alternates from centralized to fully distributed ones. Based on the degree of centralization, different: (i) scalability, (ii) stability, and (iii) optimality targets can be reached. To sustain flexible management approaches the Radio Access Network as a Service (RANaaS) concept has been introduced [112]. With the RANaaS, RAN resources are virtualized and exposed through cloud platforms. Utilizing this approach, management functionalities can be split between BSs and the cloud based on the degree of centralization that is required in any specific networking context. For sure, when BS functionalities are migrated to the cloud, some extra delay may be incurred in the execution of management operations. Therefore, that degree of centralization should be proportional to the capacity of the backhaul infrastructure.

Based on the above mentioned text, RANaaS enables: (i) dynamic wireless capacity allocation in time and space varying 5G systems, (ii) increased flexibility of management platforms due to a technology independent state representation of hyper-dense 5G deployments, (iii) new stores of management functionalities provided by third parties (i.e., new business opportunities), and (iv) easy coexistence of multiple telecommunication operators, sharing the same physical network infrastructure [112], [113].

2.3.2 5G Core Network Enablers

Finally, this section discusses the emerging network enablers which are pertinent to supporting the above 5G RAN enablers. Traditionally, core networks have been designed as a single network architecture serving multiple purposes, addressing a range of requirements, and supporting backward compatibility and interoperability. This "one-size-fits-all" approach has kept costs at a reasonable level, given that one set of vertically integrated nodes has provided all functionality. Technology has, however, evolved.

Virtualization, advanced automation and orchestration make it possible to build networks in a more (i) scalable, (ii) flexible, and (iii) dynamic way. From several possible enablers, the focus in this section is given on Software Defined Networking (SDN) and Network Function Virtualization (NFV).

Software Defined Networking

The SDN paradigm initially designed for wired networks (e.g., data centers), has recently gained a lot of attention into the wireless systems [114], and it is seen as a key technology enabler for 5G networks [115], [116]. SDN separates the data plane (i.e., the traffic forwarding between network devices, such as switches, routers, end terminals) from the control plane (i.e., the decision making about the routing of traffic flow) [117]. SDN merges network control into a logical entity, namely SDN controller, and allows programmability of the network, by external applications. With its centralized view of the network i.e., topology, active flows, etc., SDN provides dynamic, flexible, and automated reconfiguration of the network. Moreover, SDN will be able to address flexibility and interoperability challenges of future multi-vendor, multi-tenant 5G scenarios. In fact, with SDN it will be possible to deploy a vendor-independent service delivery platform, able to proactively respond to the changing business, end-users and market needs.

Therefore, SDN will simplify network design, management and maintenance in heterogeneous networked environments [118]. With the explosion of devices connected within the 5G infrastructure, traditional network architectures will not be able to manage both the volume of devices, and the amount of data they will be dumping into the network. There will be need to effectively manage the load of traffic and the network resources in the 5G era, to avoid possible collapse of the network, and allow the coexistence of different services with different QoS and QoE requirements [119].

Network Function Virtualization

The NFV stands for a complementary technology of SDN, destined to impact future 5G networks. Nowadays, NFV aims to virtualize a set of network functions, by deploying them into software packages, which can be assembled and chained to create the same services provided by legacy networks [120]. The NFV concept comes from the classical service, whereby many virtual machines running different operating systems, software and processors, can be installed on the same server. By moving network functions from dedicated hardware into general purpose computing/storage platforms (e.g., servers), NFV technologies will allow to manage many heterogeneous 5G / IoT-ready devices. Moreover, by implementing the network functions in software packages that can be deployed in virtualized infrustructure, NFV offers scalability and large flexibility in operating and managing mobile devices.

With NFV, it will be possible to reduce both CAPEX and OPEX. Currently, the use of NFV is under discussion in the context of virtualizing the core network, and centralizing the base band processing within RAN [37], [121].

3 PROXIMITY-BASED (CELLULAR-ASSISTED) NETWORKING

While telecommunication operators have finally started to deploy fourth generation broadband technology, many believe it will still be insufficient to meet the anticipated demand in mobile traffic over the coming years [4]. Generally, the natural way to cope with traffic acceleration is to reduce cell size, and this can be done in many ways. The most obvious method is via cells' densification, but this requires additional Capital Expenditures (CAPEX) and Operating Expenses (OPEX) to install and manage these new base stations. On the other hand, another approach, which avoids this additional CAPEX / OPEX, involves offloading cellular traffic onto direct D2D connections whenever the users involved are in proximity. Given that, most end devices are capable of establishing concurrent cellular and WiFi connections today, we expect the majority of immediate gains from this approach to come from the use of the unlicensed bands.

However, despite its huge commercial success, WiFi-based direct connectivity may suffer from stringent session continuity limitations, excessive user contention, and cumbersome manual setup / security procedures. In this chapter, the proposed, implemented and successfully tested integration of managed D2D communication links into current cellular technology is comprehensively described. Provided outcomes are based on a simulation tools and especially on showcasing the proposed principles in real 3GPP LTE-A wireless system located at Brno University of Technology, Czech Republic.

3.1 Data Offloading Solutions

This section (3.1) deals in the first part with the description of access procedure using the Random Access Channel (RACH) of LTE. As a complement to access procedures, the differences between the H2H and M2M communication are described. Today, the WiFi and femtocells have emerged as two most preferred offloading methods [122]. Due to the fact that most mobile operators have introduced and started to implement a mobile data offloading strategy using the AP infrastructure, in this section, the attention will be paid to mobile data offloading via WiFi technology; this approach is divided into two groups: (i) AP-based, and (ii) D2D communication [122], [123]. The classification of the available mechanisms is divided into two additional categories: (i) non-delayed offloading, and (ii) delayed offloading, see Fig. 3.1.

Described data offloading techniques were further implemented using the simulation tool Network Simulator 3 (NS-3). Within the existing research, non-delayed offloading techniques were explored and implemented. More precisely, the Access Network Discovery and Selection Function (ANDSF) mechanism (3.1.2) was practically evaluated. ANDSF mechanism represents the AP-based type of non-delayed offloading techniques and it is based on the measuring and evaluating of signal strength of the received signals from the available networks. Correct behavior of created scenario, where the data traffic was

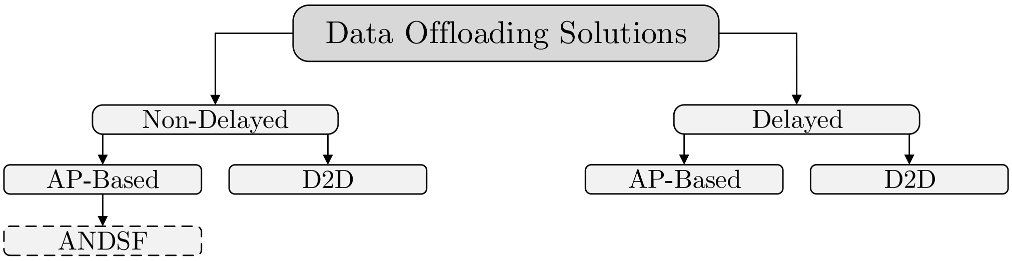


Fig. 3.1: Classification of the offloading techniques within the Chapter 3.

offloaded based on the measured signal strength, was proven by several different configurations of LTE and WiFi networks, see Section 3.1.3.

3.1.1 Communication via Cellular Networks (LTE-A)

The idea of interconnected devices operating without the human interaction has potential to create the new types of the applications and the business models. The realization of M2M systems in real world represents challenges at many levels; starting from (i) computation power, (ii) sensing, and (iii) energy harvesting to (iv) communication technologies.

The key idea of M2M communication infrastructure is to interconnect a server (running the core application and processing data) with millions of devices deployed around the world (interacting with the other machines / devices, different environments and human beings). Following the recommendations given by the European Telecommunication Standard Institute (ETSI), M2M devices will be interconnected via the cellular networks [124]. This statement includes both the access and the core part of cellular network together with M2M servers (computing devices). Contemplated scenario of M2M architecture is depicted in Fig. 3.2. The proposed architecture takes into account two different ways which can be used by M2M devices for connection to the core network [20][3]:

- Cellular connectivity: connection through access network to core networks, where each single device has their own Subscriber Identity Module (SIM) card for cellular connectivity.
- M2M networks: M2M devices may create M2M area networks using short range technologies represented by standards IEEE 802.15.6, IEEE 802.15.4(e), or IEEE 802.11. These M2M area networks can be then connected to the core networks via M2M gateways [125], [126], [127].

As mentioned in [129], the high density M2M area networks represent several challenges at the cellular level for the telecommunication operators. M2M type of communication is fundamentally different in comparison with the H2H communication, see Table 2.1 for summary of the key differences between M2M and H2H. The discussion about access mechanisms of cellular networks, where the tens of thousands of customers / subscribers per cell want to connect at the same time, is crucial for the next generation of cellular

[3] In the 3GPP terminology, the M2M devices are often called as Machine Type Communication Devices (MTCD) and M2M gateways as Machine Type Communication Gateways (MTCG).

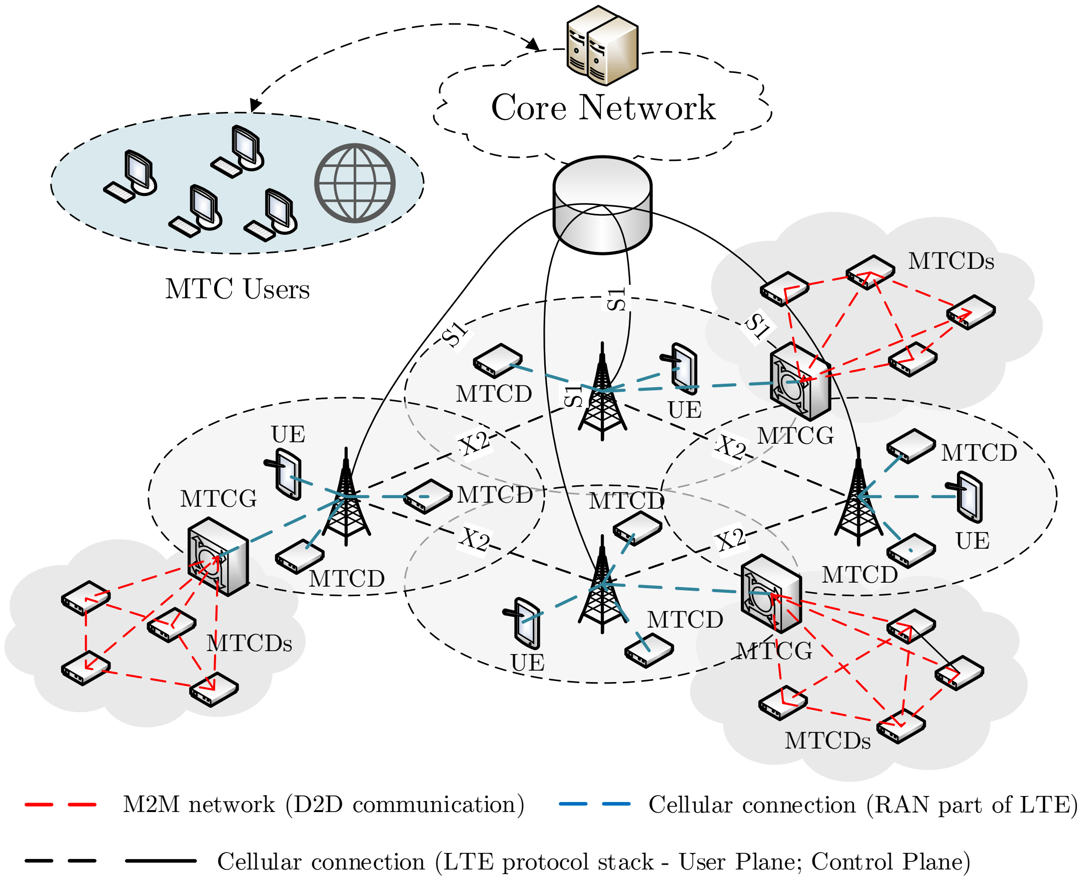


Fig. 3.2: LTE networks with M2M communications [128].

networks [129]. Today, the attention mainly focuses on a question how to properly use the RACH of LTE and LTE-A. In [130], the detailed description of the following RAN control mechanisms is given; *PUSH based methods* (Randomized access dispersion, Differentiated services provision, Dedicated resource allocation), *PULL based methods* (paging method, contention-free method).

The M2M devices must trigger the access procedure to the base station (Evolved NodeB (eNB) in case of LTE network) in the following situations [131]:

1. During the initial access to the network (association process).
2. When receiving or transmitting (new) data and the M2M is not synchronized.
3. Upon transmission of data when no scheduling request resources are configured (for the uplink control channel).
4. In case of handover procedure; to avoid a session drop.
5. When a radio link failed; re-establish the connection.

For managing the above mentioned situations, two different mechanisms of Random Access (RA) procedure are defined in LTE Release 8 [131], [132], see Fig. 3.3:

- **Contention-based:** devices compete for the channel access. In this approach the collisions may occur, therefore this type of access is considered for delay tolerant access requests. As an example of this approach, the connection of UE to the LTE network can be mentioned.

- **Contention-free:** eNB allocates a set of the specific access resources that must have high priority / high probability of success (delay aware) e.g., handover between two eNBs.

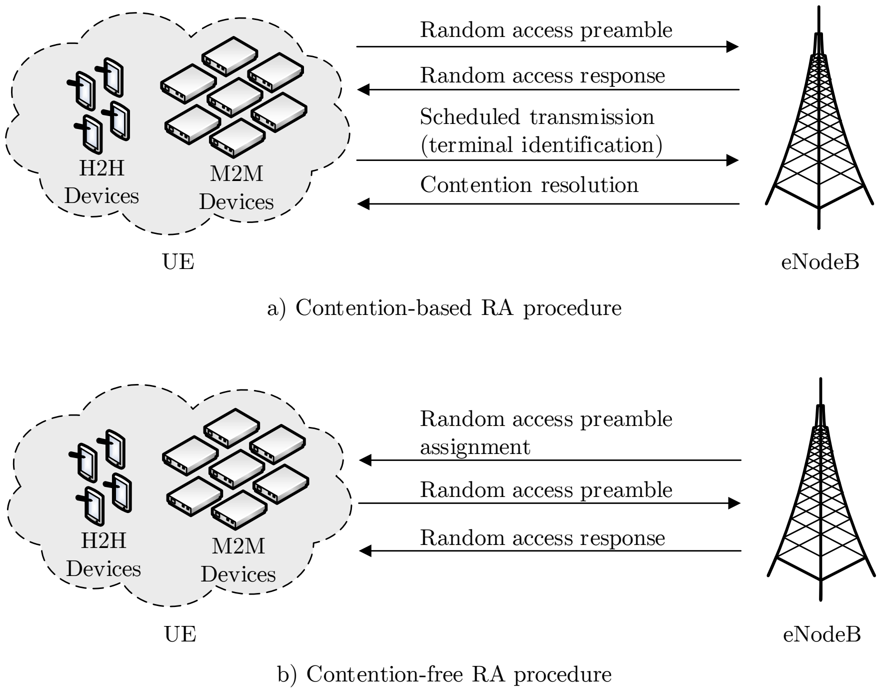
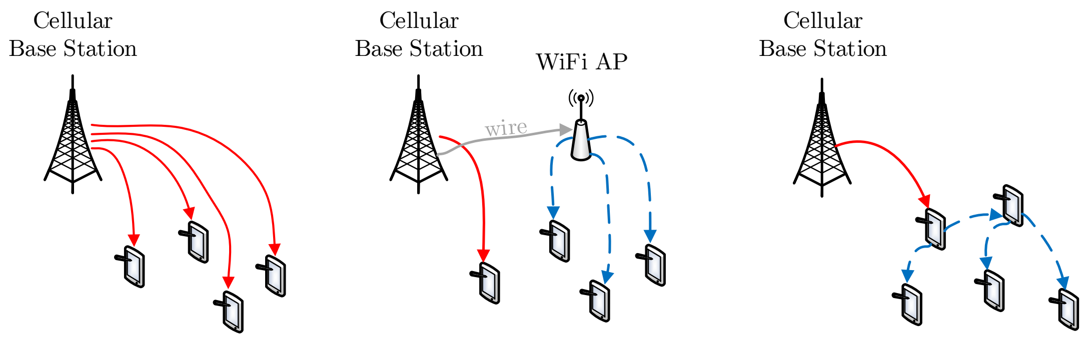


Fig. 3.3: Random access procedures in LTE network.

3.1.2 Cellular Data Offloading Approaches

For the better understanding of the described issue, the selected approaches of cellular data offloading are compared in Fig. 3.4 with the traditional infrastructure-only architecture of cellular network.

Switching a certain part of data traffic over the fixed WiFi access point, as depicted in Fig. 3.4(b), represents the conventional way, how to reduce data traffic within cellular networks. Customers located within the coverage area of AP can use this additional wireless network as a valuable alternative for data exchange (the possibility to switch seamlessly between two heterogeneous networks is called vertical handover [133]). APs generally provide higher connection speed and network throughput in comparison with the cellular networks [134]. On the other hand, in case of APs, the coverage is limited and the mobility is a question of area defined by individual AP. Therefore, there are limitations (chiefly due to the limited coverage area), the monetary cost of deploying a set of APs is still lower than deploying even one new cellular base station. Based on this fact, the leading telecommunication operators as AT&T, Verizon, and T-Mobile have started



(a) Infrastructure only (b) AP-based offloading (c) Device-to-device offloading

Fig. 3.4: Two major approaches (AP-based and D2D offloading) to cellular data offloading in comparison with the traditional infrastructure-only concept.

an integration of the number of APs (utilizing the IEEE 802.11 standard) in their cellular networks [135].

Following the information given in [4], the popularity of using smartphones will not stop during the next four years. Based on the fact that smartphones represent the target group of devices which will perform the data offloading procedures, it is obvious that the offloaded volume is bounded with smartphones penetration – as discussed in Chapter 2. The increasing popularity enables the alternative communication options; besides the AP-based offloading techniques, the new approaches called D2D networks or D2D communications are emerging. D2D networks, as depicted in Fig. 3.4(c), can work without the infrastructure backbone. This innovative technique has potential to be the leading topic of data offloading. This approach could benefit from the shared interests among the customers. Telecommunication operators may decide to send requested content only to a very small subset of customers via cellular network [136] and then let customers spread / resend information through their D2D connection, see Fig. 3.7.

It is important to notice that both forms of data offloading (AP-based and D2D communication) may be implemented concurrently when they will enable customers to retrieve data in *hybrid* mode.

Beyond the differences between the AP-based and D2D approaches, there is another aspect which should be taken into account – requirements of the applications generating traffic in terms of delivery guarantees. Depending on delay (content delivery time) it is possible to divide offloading techniques into two categories: *non-delayed offloading* and *delayed offloading* [123].

Non-delayed Offloading

Non-delayed offloading represents one of the most experimented offloading techniques. In case of this technology, it is possible to manage real-time and interactive data which enables to use this mechanism for services as video streaming or Voice over IP (VoIP).

Telecommunication operators can motivate the customers to offload their data by offering e.g., unlimited data through WiFi APs.

From the technical point of view, current cellular base stations are able to cover *macro* areas ($1-2$ kilometers of diameter in urban areas and up to 20 kilometers in rural areas). Conversely to cellular base stations, AP can cover areas in the range of $30-100$ meters. For better imagination, LTE can reach at maximum several tens of Mbps in realistic conditions [134]. On the other hand, in comparison with LTE, standard IEEE 802.11 in the latest version can reach in real conditions throughput up to 40 Mbps [134].

In case of D2D, additional classification could divide D2D offloading approaches into two categories [123]:

- Out-of-band: solutions rely on alternative unlicensed communication technologies. For the out-of-band, the IEEE 802.11, Bluetooth and IEEE 802.15 represent the most preferred choices.
- In-band: A dedicated part of licensed cellular band is used for D2D communication. For the in-band offloading category, the recent development of the 3GPP LTE-A standard (Release 12) suggests to implement D2D communication into the future cellular architecture [137]. Nevertheless, D2D technologies today use the unlicensed bands (like WiFi and Bluetooth) [122].

AP-based A common model for AP-based offloading is *user-driven* (customers have to explicitly enable the alternative access network / alternative wireless interface). This is the first option because it does not require modifications in the cellular network infrastructure. The common drawbacks as limited coverage in case of WiFi were described in section 3.1.2. To improve the customer experience (QoE, QoS), the current trend is to let telecommunication operators implement sophisticated control of the offloading process, see Fig. 3.5.

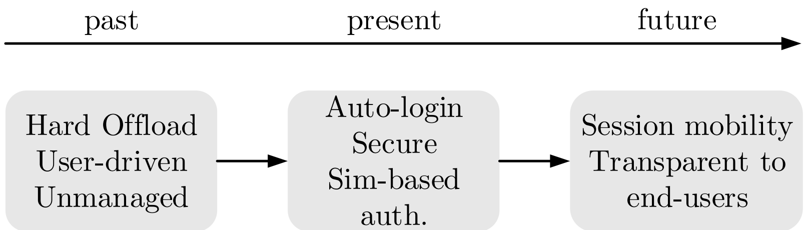


Fig. 3.5: Integration of alternative access networks in parallel with cellular infrastructure.

The integration process, which means partnerships between the cellular and wireless providers, includes common billing and accounting policies, authentication, authorization, accounting (often called AAA) and shared subscriber databases [123].

For the optimal implementation of non-delayed AP-based offloading mechanisms, the following criteria should be taken into account:

- AP Deployment and Modeling: optimal deployment of APs can serve in short term for improving the key attributes (i.e., throughput) of data offloading. The questions of AP deployment were discussed in detail in the literature [138], [139], [140], [141],

[142]. As an output, in ideal case, up to 70 % of data traffic could be offloaded through the cautiously planned AP deployment. The main research area (based on the previous papers) deals with the selection of the optimal AP in case more APs are available at the same time. This question is related to the Access Network Discovery and Selection Function (ANDSF) mechanism, which will be introduced later in Section 3.1.2.

- 3GPP Standardization Efforts: in the LTE network, the Evolved Packet Core (EPC) flat architecture fulfills the requirements for the hybrid network is introduced. The goal of the EPC is to provide the access-independent IP based architecture which will be capable of providing the switching / handover between IP based services. The proposed mechanisms can be nearly transparent for customers (end-users) and both 3GPP and Non-3GPP radio access network technologies are supported. The 3GPP treats data offloading as a key mechanism to overcome the cellular overload problems [123]. As a possible solution, the ANDSF mechanism, which can manage switching between different access technologies, was proposed [143]. The ANDSF framework manages the communication between the customer (mobile device) and cellular system, where framework can perform network selection and traffic routing from cellular to another available wireless network (WiFi, WiMAX, etc.) [144]. Three different selection strategies can be used: (i) the area coverage, (ii) the signal-to-noise ratio (SNR), and (iii) the system load. This framework is described in more detail later in following Section 3.1.3. Besides the ANDSF framework, three another data offloading mechanisms (not discussed in this dissertation thesis) based on hybrid architecture of EPC were developed[4]:
  - Local IP access (LIPA) [145].
  - Selected IP traffic offload (SIPTO) [146].
  - IP flow mobility (IFOM) [147].
- Multi-Interface Integration and Transport Protocols: simultaneous use of multiple access network technologies represents the very important part of data offloading. In case of non-delayed offloading, it is crucial to have communication stacks capable of supporting the features as multiple instantaneous connections, data aggregation or inter-technology switching. Today, the extensions to standard protocols e.g., Stream Control Transmission Protocol (SCTP) [148] or Multipath Transmission Control Protocol (MPTCP) [149] enable the aggregation of bandwidth offered by in-range network technologies and seamless switching between these technologies. Even if some new protocols were developed (e.g., SCTP and MPTCP), the process of implementation of these protocols, which can handle in parallel multiple data flows on separate interfaces on mobile device into the standards, has not been finished yet. Therefore, the common transport protocols as Transmission Control Protocol (TCP) or User Datagram Protocol (UDP) are still used [123].

[4]Other data offloading mechanisms were proposed by 3GPP e.g., Multiple Access PDN Connection (MAPCON) which works only with trusted Non-3GPP radio access networks.

D2D D2D communication represents, in comparison with the AP-based offloading, a special type of data offloading which uses available multiple interfaces of mobile devices to deliver requested data traffic. Initially, the out-of-band (see Section 3.1.2) transmission was taken into account. Nevertheless, actual development in this direction implies that 3GPP LTE standard (Release 12) integrates the direct in-band communication between the mobile devices [150]. The advantages of D2D offloading represented by higher average throughput, area coverage extension and energy consumption stand against higher complexity (e.g., difficult compliance of QoS guarantees if the devices are not stationary nodes, modification of signaling in core network)[5].

Delayed Offloading

The second option for the data offloading represents delayed offloading which can be used in use cases where it is not crucial to receive data within the strictly limited time interval (e.g., e-mails). The selected data is forwarded only when the communication between users or APs is occasionally established [151]. During the initial communication between the devices, the *inter-contact time* provides the information about the delivery capacity inside the opportunistic network. Next, when the communication occurs, knowing the information about the duration of the previous contact / communication (*contact-time*) helps to predict how many data can be sent (the amount of transmitted data is affected mainly by competition of users for the same wireless channel) [152].

In the previous Section 3.1.2, the implementations of AP-based and D2D communication techniques were described with respect to Non-delayed offloading. In this part, the description of AP-based and D2D as a delay tolerant data offloading services is given.

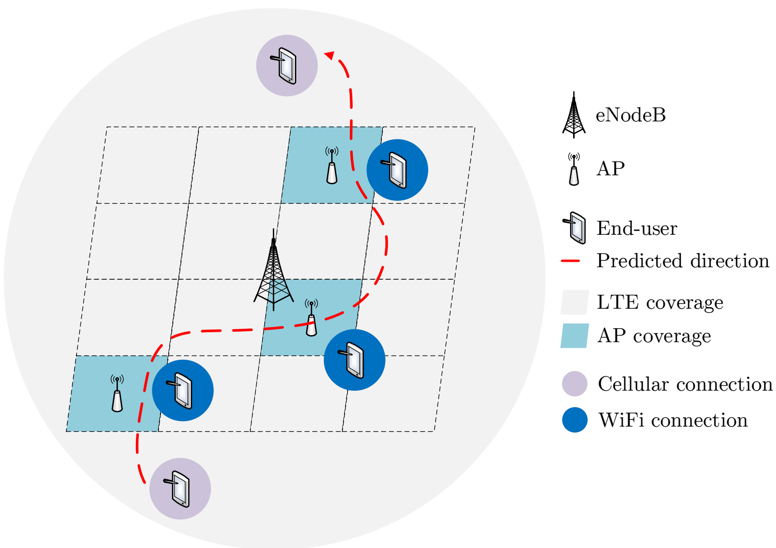


Fig. 3.6: Delayed offloading - coverage of various network technologies.

[5]Real full scale practical scenario of network assisted WiFi-Direct on running 3GPP LTE deployment was demonstrated in [34].

AP-based As depicted in Fig. 3.6, the AP-based data offloading uses additional networking backbone (today often based on IEEE 802.11 APs) to deliver the delay tolerant data traffic out of cellular network. APs could be a part of cellular network infrastructure or may be independent of cellular network. The possible contact between end-user and fixed APs defines the offloading capacity of the network. The considered scenario of this data offloading technique is shown in Fig. 3.6, where the UE moves along the selected path (*red line*). In case UE is in range of WiFi network, connection between UE and AP is established and data is sent (*blue circle*). Based on the fact that the delayed offloading is used here, the remaining data (if any) will be sent when the WiFi connection will be again successfully established; in case the probability of future connection to AP is very low, the data is then sent via the cellular network (*purple circle*).

Currently, the attention focuses on future offloading prediction (using the information from past behavior of users – mobility, duration of the previous communication, network throughput). Using the prediction, the offloading coordinators (telecommunication operators) are able to decide, which part of data will be offloaded to which AP. This strategy is adopted also for downloading, where the requested content is divided into the several parts which are subsequently sent to APs located in the predicted path of the end-user. The two above mentioned approaches will be described at the length of following lines.

- Prediction-based offloading: the key requirements for this type of offloading determine the future capacity of WiFi networks and movement of the mobile devices. A decision to wait for next possible offloading opportunity (via WiFi) instead of sending data via the cellular network is not so critical in case of delayed offloading, which is based on knowledge of mobility of end-user, locations of available APs and available bandwidth [153]. As the most promising framework based on the principles of delayed offloading, the Metropolitan Advanced Delivery Network (MADNET) is mentioned very often [122]. MADNET represents the network centered architecture which enables cellular, WiFi and, D2D communication.
- Feasibility and AP Deployment: the problem of optimal AP's deployment can be compared with the Intelligent Transportation Systems (ITS) [154]. The current research outputs given in [155] and [156] propose cost based analysis for the optimal trade off between the number of APs and offloading ratio. In [138], dependence between increasing the delay tolerance and ratio of successfully offloaded traffic is discussed.

D2D Delayed D2D offloading represents the option, where the data traffic is transmitted directly by end users. This offloading type can serve as an inexpensive way how to increase mobile network capacity and handle large amounts of data. The principle lies in fact that some very popular content is requested by a large number of end users, who are located close to each other [157]. Without D2D offloading, the RAN part of LTE network can be overloaded (e.g., during the big social event as a concert or a sport match). Conversely, using D2D offloading content is sent only to a small group of users, who are located among users, who requested specific content, but not necessarily at the same time [158]. Being able to select the seed nodes with high probability increases the performance of the offloading strategy. Therefore, the performance of the offloading algorithms depends heavily on the understanding of system dynamic / system behavior.

The typical example of delayed D2D offloading is depicted in Fig. 3.7. The users, who received the requested content from cellular network, are often called *seeds*. These users propagate downloaded content to users who are in their communication range (*opportunistic users*). Based on the information given in [123], as one of the most promising framework seems to be Traffic Offloading with Movement Prediction (TOMP) [136]. TOMP manages communication between the devices based on information about position and velocity of UE. Framework selects as a seeds the users, who have the best future connectivity with other UEs (based on the movement prediction). As a metric, TOMP introduces three coverage metrics for future movement prediction of UE: (i) free space coverage, (ii) static coverage, (iii) and graph based coverage.

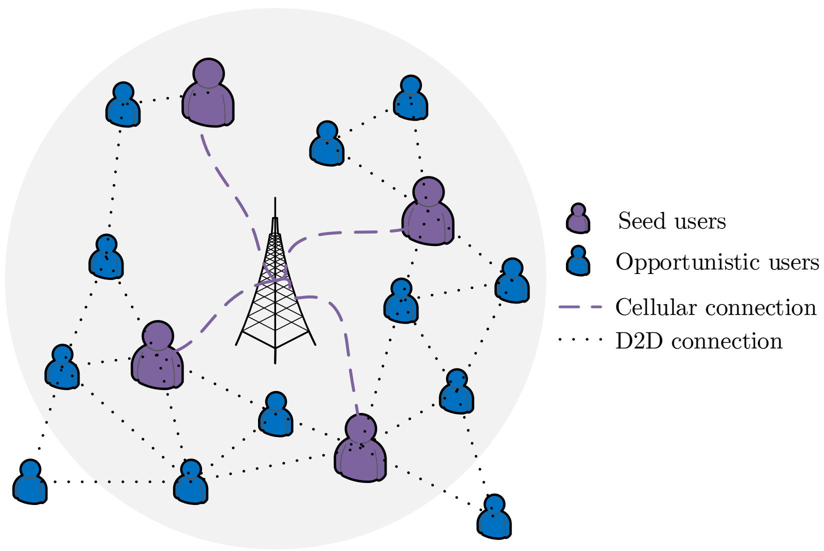


Fig. 3.7: D2D offloading via delay tolerant networks.

3.1.3 Implementation ANDSF Offloading Mechanism in NS-3

As described in Section 3.1.2, the simulation of data offloading mechanism within this dissertation work focuses on implementation the ANDSF in simulation environment NS-3. More precisely, the NS-3 [159] in version 3.21 was used together with the framework *LTE-EPC Network Simulator* (LENA) [160]. The created scenario, where the ANDSF data offloading mechanism is implemented, is depicted in Fig. 3.8.

A description of the 3GPP network architecture with adopted ANDSF entity is shown in Fig. 3.9. The untrusted access network can be connected with the ANDSF either via the local Mobile Network Operator (MNO) access node or through the core part of LTE. The mentioned S14 interface manages sending of discovery information (i.e., the lists of prioritized available networks in the range of UE), Inter-system Mobility Policy (ISMP) (i.e., rules for selection of one active access network), and Inter-system Routing Policy (ISRP) (i.e., rules of access selection for potentially multiple simultaneous IP connections).

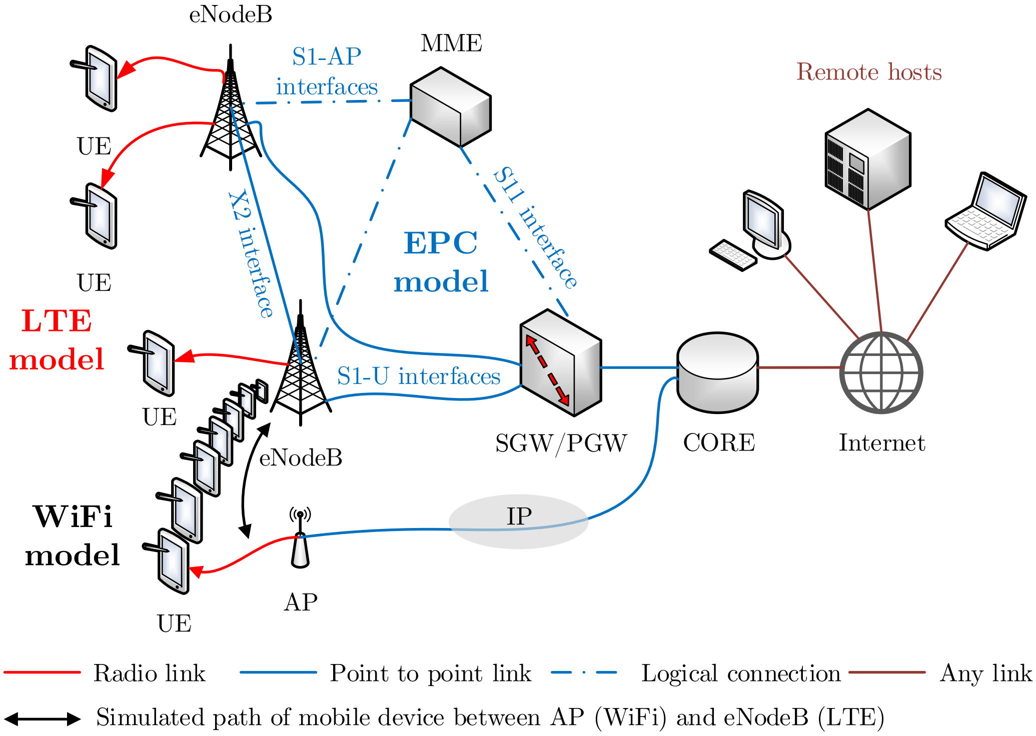


Fig. 3.8: Topology of created scenario - ANDSF mechanism.

Fig. 3.10 shows the implementation of the end-to-end LTE - EPC data plane protocol stack of LENA framework (in NS-3) which was implemented as a data offloading mechanism in this work. The biggest change in comparison with the standard implementation of data plane protocol stack of LTE is the merge of the Serving Gateway (SGW) and PDN Gateway (PGW) functionality within one single (SGW)/(PGW) node in NS-3. This change causes that there is no need to have S5 and S8 interfaces which are specified by 3GPP. The S1-U protocol stack and the LTE radio protocol stack, specified by 3GPP, are also detailed in Fig. 3.10.

General Description of Implemented Scenarios

The topology of the implemented offloading scenario, see Fig. 3.8, contains one IEEE 802.11g AP and one eNB as two main network access nodes. These two nodes are in distance of 300 meters. Between these two nodes, the mobile device representing end device with two active wireless interfaces is located[6]. The UE is moving at speed of 1.5 m/s from the AP to the eNB. When the UE reaches the coordinates of eNB, the

[6]The implementation of two active wireless interfaces between the WiFi and LTE networks in NS-3 was never done before and this implementation will be added within the next releases of NS-3.

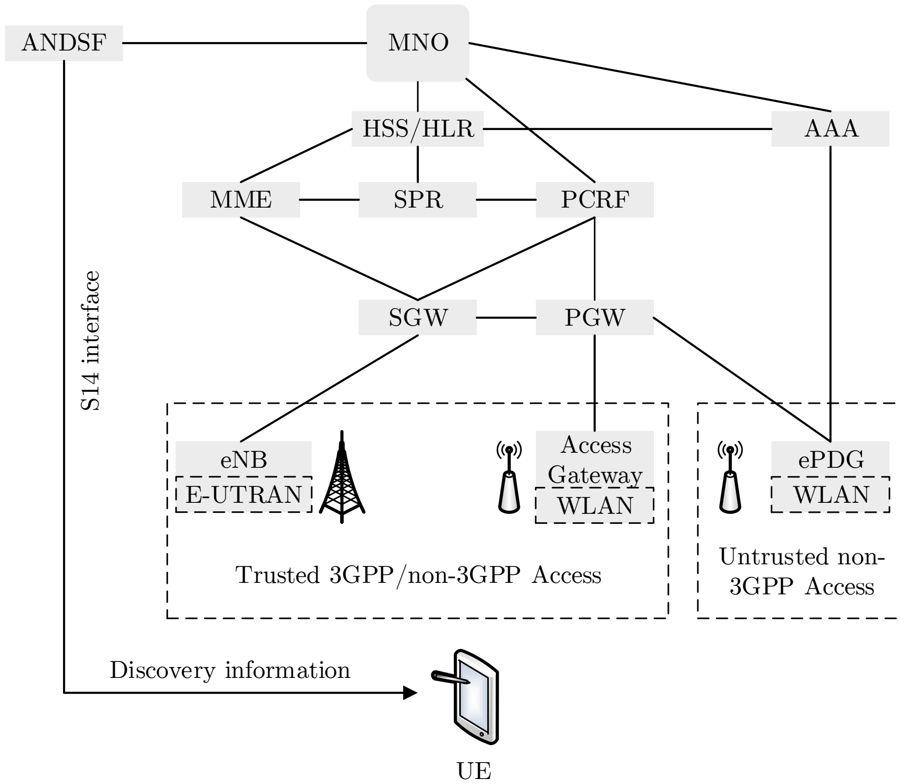


Fig. 3.9: 3GPP network architecture adopting ANDSF entity.

direction is changed back to the position of AP. Utilized system parameters (with respect to the created simulation scenarios in NS-3) are listed in Table 3.1, Table 3.2 and Table 3.3.

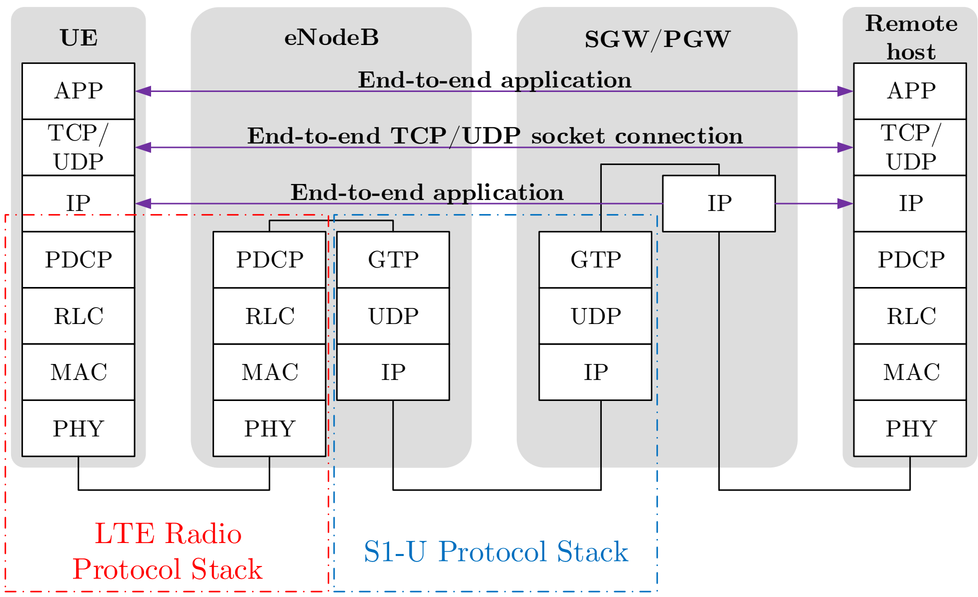


Fig. 3.10: LTE-ECP data plane protocol stack in LENA framework.

Parameters of Simulation Scenario

Tab. 3.1: Parameters of LTE network in NS-3

Parameter	Settings/Value
Cell Layout	1 eNodeB, 1 sector
Duplex Format	LTE-FDD
Maximum transmit power	30 dBm
System Bandwith	3 MHz ($\sim$ 15 PRBs); 5 MHz ($\sim$ 25 PRBs)
EPS bearer	NGBR Video TCP Default
Scheduler	Pf Df Mac Scheduler
Path loss model	Friis Spectrum Propagation Loss Model
Direction	Download
eNB antenna model	Isotropic Antenna Model
Frequency Reuse Factor	1

Tab. 3.2: Parameters of UE in NS-3

Parameter	Settings/Value
UE maximum transmit power	10 dBm
UE antenna model	Isotropic Antenna Model
UE velocity	1.5 m/s
Number of UE	1

Tab. 3.3: Parameters of data traffic in NS-3

On/Off application (Data traffic)	
Transport protocol	UDP
File Size	1 400 B
Data rate	54 Mbps

Offloading of Data Traffic Based on SNR

The first implemented method of ANDSF data offloading mechanism is based on continued measuring of the SNR value. Based on the outputs from the previous work [161], the threshold value was chosen to 10 dBm for LTE channels with bandwidth 3 MHz (15 RB; Resource Blocks) and 5 MHz (25 RB). The value of the SNR is measured in the loop every half second. Pseudo-code of implemented mechanism is given in following lines. The results are shown in Fig. 3.11 and Fig. 3.12.

It is possible to state that the UE is connected to AP (WiFi networks) up the distance 117 meters from AP. At this point, the value of throughput is equal to 1.68 Mbps. Beyond this distance, the UE switches the technology from WiFi to LTE and the throughput is then constantly 8.5 Mbps for 3 MHz; 16.08 Mbps for 5 MHz channel bandwidth. At the point where the UE reaches the position of eNB it goes back to the position of AP.

Pseudo-code – offloading data traffic based on SNR value

Input: WiFi_SNR
Output: Activate appropriate wireless interface

Initialization of available interfaces;

if *WiFi_SNR > snrThreshold* **then**

    Calculate throughput of WiFi network;
    Save actual SNR for WiFi;
    Activate the WiFi wireless interface;

else

    Calculate throughput of LTE network;
    Save actual SNR for LTE;
    Stay connected via mobile network;
    Keep the WiFi interface in standby mode;

end

Repeat measurement of SNR value;

Algorithm 1: Logic for offloading data traffic based on SNR value

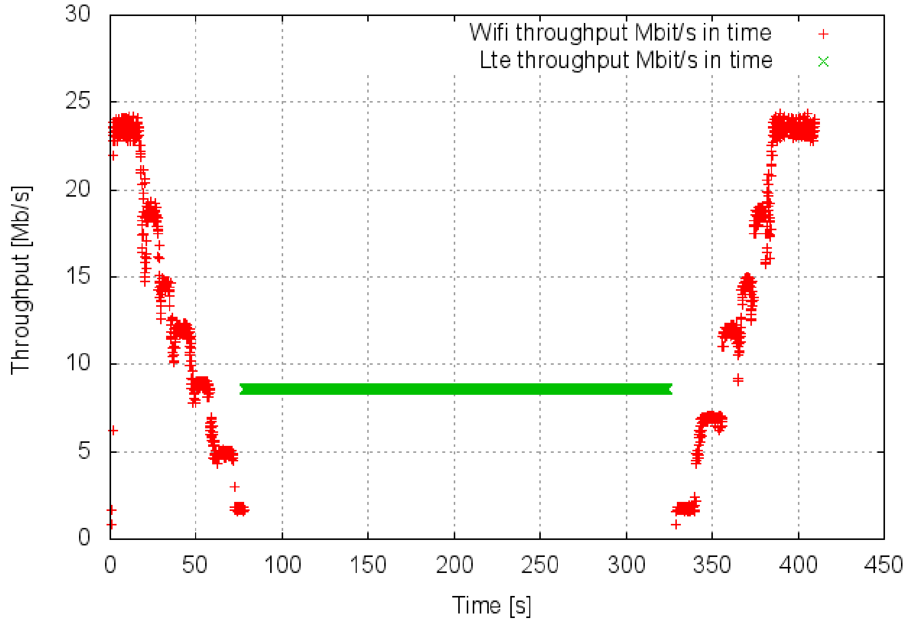


Fig. 3.11: Offloading of data traffic using SNR, 15 RB [162].

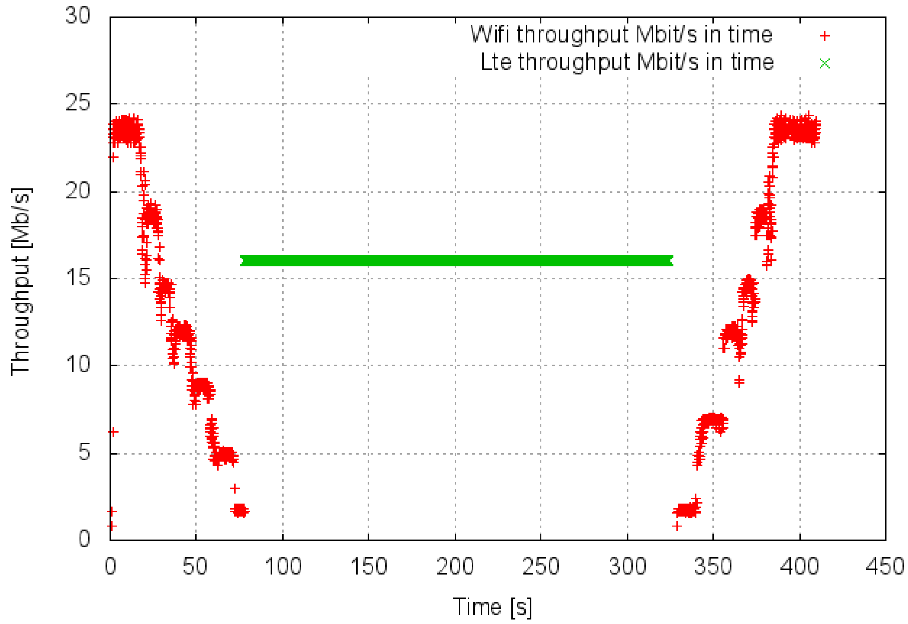


Fig. 3.12: Offloading of data traffic using SNR, 25 RB [162].

Offloading of Data Traffic Based on Network Throughput

Following behavior of the first implemented method, see Fig. 3.11 and Fig. 3.12, the second method of ANDSF data offloading mechanism, which improves the decision logic for switching data traffic between two independent networks, was implemented.

The potential issue of the first scenario seems to be the situation when the SNR is better in WiFi network than in LTE, which based on the implemented logic, initiates the switching from the LTE network to WiFi network, but the real values of data throughput are lower than in case of cellular network (e.g., due to the high number of connected mobile devices in WiFi network). This problem also occurs vice versa, see Fig. 3.11 and Fig. 3.12.

Following the above mentioned facts, the ANDSF data offloading mechanism based on the real throughput as the key decision factor can provide better overall performance under specific network conditions. Offloading of data traffic based on the values of network throughput uses the algorithm, which at the beginning of the simulation measures the throughput of available wireless networks in the range of mobile device. During the simulation, the measurement of actual throughput value is performed in loop every 0.1 seconds – for the better evaluation, the separated simulations for each type of ANDSF data offloading mechanism were performed.

In case of data offloading based on values of throughput, see Fig. 3.13 and Fig. 3.14, the offloading was activated for 3 MHz channel in distance of 73 meters (at 50 seconds of simulation time) from the AP, when the throughput of WiFi dropped under the throughput of LTE network. It can be seen that in distance range from 73 to 83 meters from AP (WiFi network) (at simulation time 45 – 60 seconds), the switching between the networks was performed very often.

This behaviour is known as a *ping pong* effect when the similar values of throughput for the available networks were measured. In this work, this behavior was fixed by the definition of the minimum service operation time period for both RAN technologies to 3 seconds – implemented guard interval avoids any signaling overhead or extra energy consumption caused by unnecessary switching between different radio technologies.

Pseudo-code – offloading data traffic based on network throughput

Input: Throughput of WiFi, LTE
Output: Activate appropriate wireless interface

Initialization of available interfaces;
Calculate throughput of LTE network;
Calculate throughput of WiFi network;

if *WiFi_Throughput* > *LTE_Throughput* **then**
    Save actual value of the WiFi throughput;
    Set WiFi as primary interface;
    Keep LTE interface in standby mode;
else
    Save actual value of the LTE throughput;
    Keep LTE interface as primary;
    Keep WiFi interface in standby mode;
end

Algorithm 2: Logic for offloading data traffic based on network throughput

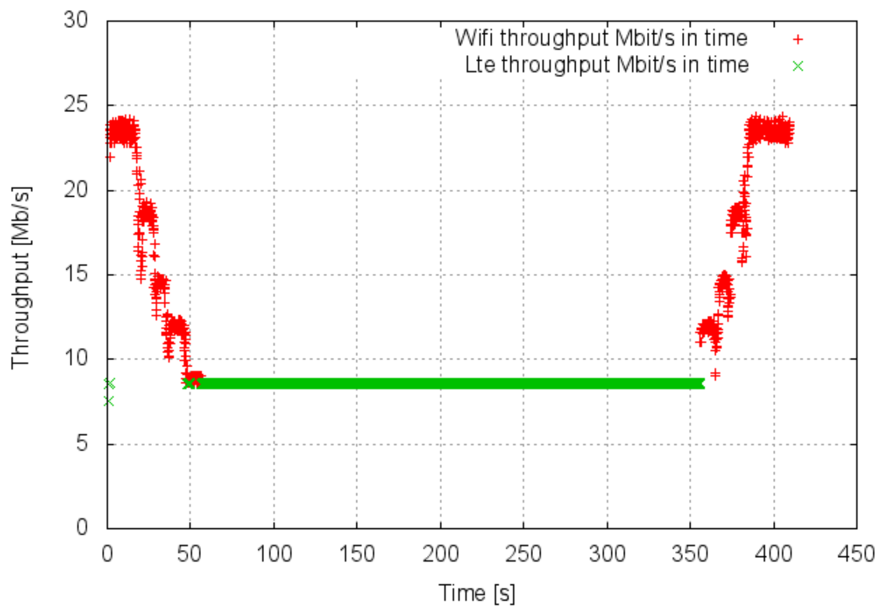


Fig. 3.13: Offload of traffic using network throughput, 15 RB [162].

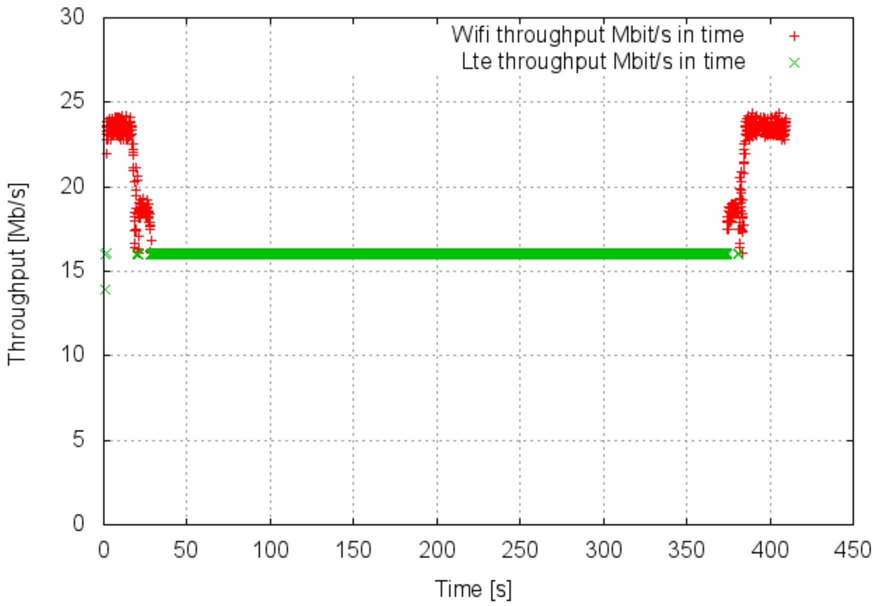


Fig. 3.14: Offload of traffic using network throughput, 25 RB [162].

3.2 Experimental Evaluation of 3GPP LTE-Assisted D2D Communication

Today's cellular network deployments can be considered as nearly ubiquitous – they provide a wide range of advanced services and are constantly evolving to serve the increasing subscriber populations. However, their ability to meet user expectations (QoS and QoE) is at risk given the constant influx of new customers and the increasing numbers of multimedia service requests [4]. Another problem for network users is the limited battery budget of their mobile devices; this becomes a serious limitation for many throughput-hungry applications. Both of these problems require significant changes in the way we approach wireless content delivery.

Traditional solutions primarily focus on increasing density of cell deployment. Owing to shorter radio links, smaller cells provide higher bit rates and require less energy for uplink transmission, especially in dense urban environments [34]. However, deploying larger numbers of smaller cells can become prohibitively expensive, and the complexity of interference management may increase much over what is desired.

In contrast, proximity-based communication between client devices enables shorter radio links without the cost of additional infrastructure [163], [164]. With such shorter and lower to the ground links, their interference is easier to manage when compared to standard infrastructure small cells. Thus, in this section, it is proposed that whenever possible, client devices use their direct connectivity capabilities, instead of cellular links. In particular, the corresponding benefits of WiFi-Direct technology [165] are highlighted, since it is already available on most client devices and does not reuse the more expensive cellular bands. With respect to this, the use of infrastructure network-assisted device discovery (by example of 3GPP LTE), which expedites the discovery process resulting in greater success probability and improved energy efficiency [163], is explored.

With this section, it is demonstrated how cellular traffic can be effectively offloaded onto WiFi-Direct D2D links and provide the estimated gains in energy efficiency and capacity from such offloading. According to existing research, certain applications, in particular Peer-to-Peer (P2P) and socially-oriented ones, could utilize such links effectively [166], [167]. This approach is based on developed advanced System-Level Simulation (SLS) toolkit, capable of capturing dynamic multi-radio scenarios, with realistic user mobility and traffic arrival patterns. It is shown, how the shorter range and simpler protocol of network-assisted D2D communications allow users to benefit from higher data rates over short distances without compromising their battery life – in this particular research, one of the forms of network assistance, when the network informs the clients only about potential D2D partners, is utilized [164].

3.2.1 Topology of D2D Communication Links

As Fig. 3.15 suggests, D2D links achieve highly diverse performance across a given deployment. They range from being orders of magnitude better than LTE to being practically unusable. Therefore, this work tries to identify certain categories of D2D links that perform well. In addition, another case, where interaction with existing WiFi networks by positioning a number of access points (APs) throughout the deployment is studied – each AP has five legacy clients that are streaming data to it. The APs and their clients make up a set of rogue nodes that are not managed in any way by the LTE network and only consume resources, which could have been, otherwise, available for WiFi-Direct communications.

Since intended D2D links are deployed randomly and may thus be affected by interference from the other transmissions, network throughput is used as main performance metric. This allows us to filter out the D2D links that have, for instance, the data rate of more than 5 Mbps (so they are guaranteed to be faster than the best LTE link) and study their topology separately.

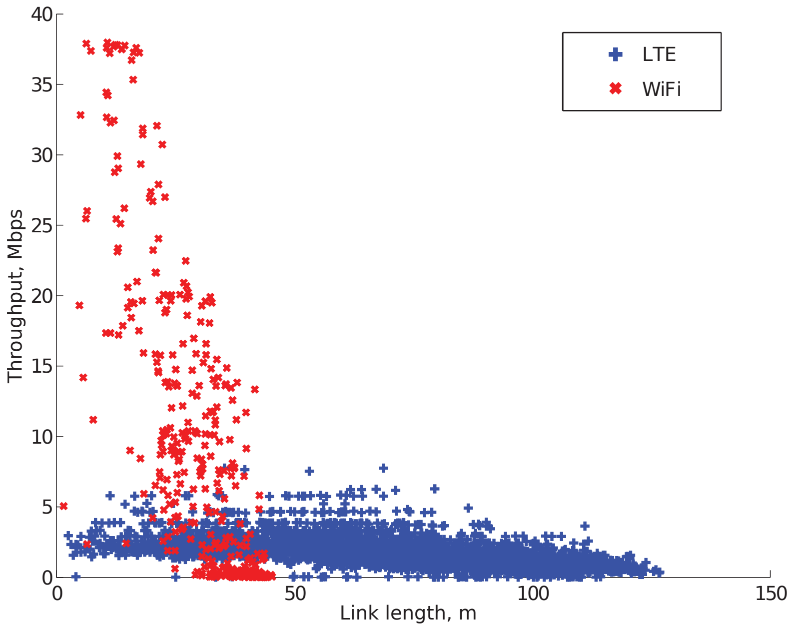


Fig. 3.15: WiFi vs LTE uplink throughput scatter plot [34], [168], [169].

Proposed studies demonstrate that D2D connections, which achieve the target rate of 5 Mbps, are primarily within the 40-meter range. According to Fig. 3.16, such D2D links are generally around 25 meters long, depending on the density. One important observation is that extremely short links are not necessarily the most likely ones to achieve the highest data rates, due to the low probability of D2D partners positioned so close to each other. Interestingly, the distribution is almost unaffected by the number of interfering links, although they do reduce system throughput by almost 50%.

Further, Fig. 3.17 also highlights that interfering neighbors can actually reduce the D2D link performance up to a point when it is no longer usable. However, when interference is not a serious issue, the WiFi-Direct path outperforms the infrastructure path even at very long distances regardless of user locations with respect to the LTE base station.

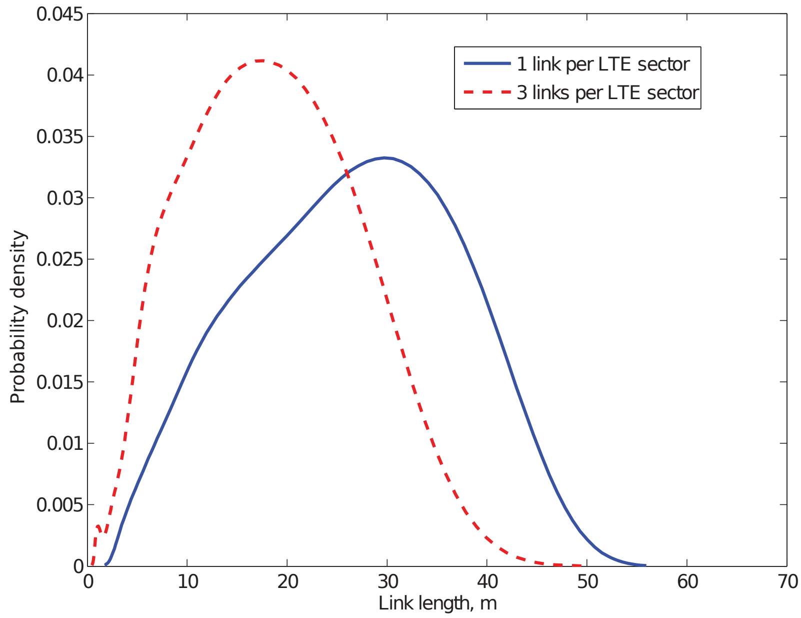


Fig. 3.16: WiFi links with rates over 1 Mbps, length distribution [34], [168], [169].

This is interesting because intuition would suggest that the further you are from the base station, the longer the WiFi link can be, and still outperform the LTE infrastructure path. However, performed research points out that the WiFi-Direct path is significantly better than the infrastructure path regardless of how close the users are to the base station even at very long inter-user distances until such point that the WiFi-Direct link simply does not work.

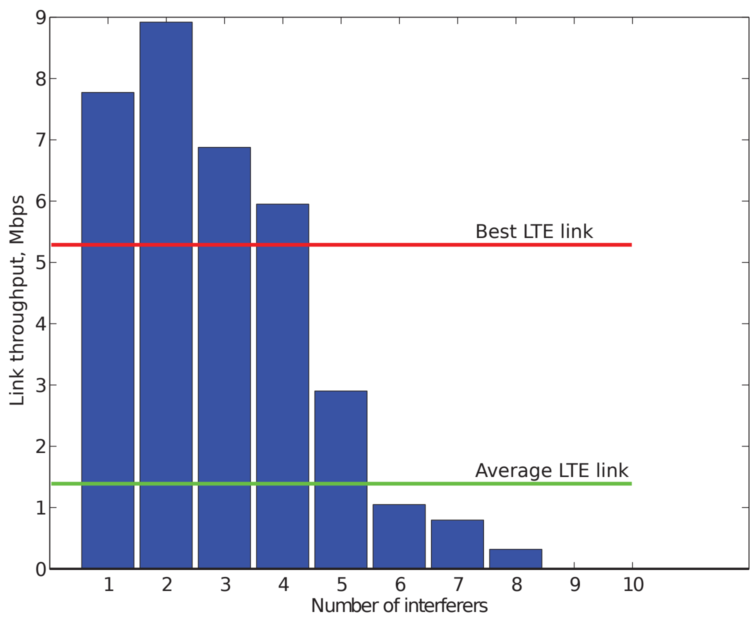


Fig. 3.17: WiFi throughput as function of interferer count [34], [168], [169].

The reason behind that is the following – unlike in cellular technologies, WiFi cannot continuously track every receiver. Instead, transmissions of nearby neighbors often mask transmissions from faraway users. As a result, there is a certain distance at which messages can no longer be decoded; at this point, communication "breaks" even though some data packets may still get through. So, unlike LTE, where the link performance degrades gradually with distance, WiFi links have nearly on/off behavior; they either perform really well (orders of magnitude better than LTE) or barely work at all. Generally, if we were to put a significant number of interferers on a regular grid, and start to measure WiFi throughput as a function of link length, we would see a clear range dependency, very similar to LTE. However, in a realistic, non-regular network, where the topology is random, this type of range-dependent behavior is not observed. In Fig. 3.15, there exist long links that perform very well, while some short links are jammed by interference. This can be illustrated clearly by observing the variance of the D2D link throughput.

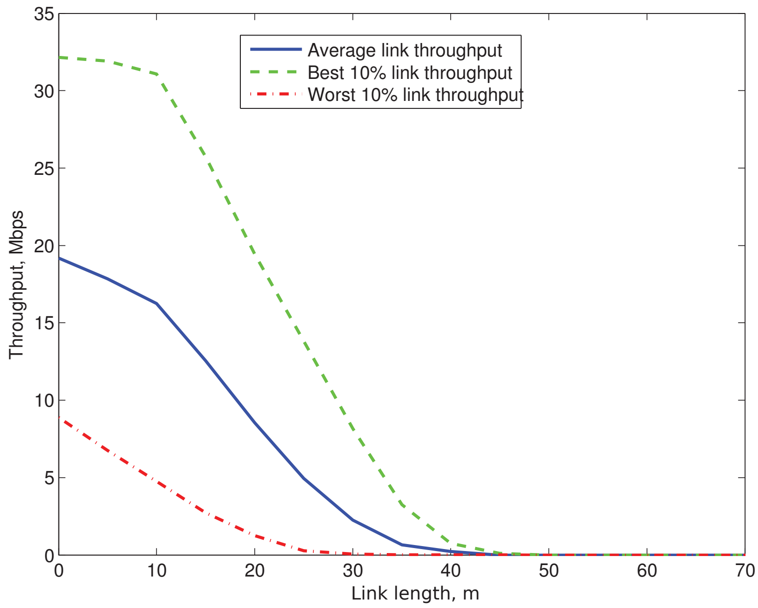


Fig. 3.18: Best 10%, worst 10% and average D2D link throughput [34], [168], [169].

Fig. 3.18 shows the data rates (in terms of average, best, and worst 10%) of WiFi-Direct links (grouped by length). It confirms that although there is a certain limit on D2D link length, throughput is mostly affected by competition over the link, rather than link length. Based on above, it can be concluded, that no matter where a client is in the cell, the D2D link (especially if it is one of the best links) is a better alternative than the LTE path, unless it is disabled by interference. We can also conclude, that the D2D performance can vary greatly, even for the same link length (this issue can be addressed through appropriate scheduling [170]).

Unlike LTE, where the best link was about twice better than the worst, here the best link can be as much as 5 times faster than the worst one, which implies that a proper scheduling algorithm (similar to approaches taken in [171]) could make use of such variation in link performance.

3.2.2 Enabling LTE Offloading onto WiFi Network - Simulation Results

If we assume (extending the proposals in [172]) that the cellular network can help its users in determining when/if a partner of interest (i.e., one with which they want to communicate) is in proximity, users can quickly and efficiently move their traffic sessions onto D2D links, thus increasing their data rates and offloading the cellular network traffic. As a result, the clients using D2D links will be able to enjoy the improved transfer rates delivered by the shorter links.

In practice, of course, protocols will have to be developed to allow the cellular network and the client device to negotiate the offloading process and ensure service continuity. However, in this section (simulation comparison) we assume these protocols exist, and that some percentage of active LTE users have decided to move their traffic sessions to D2D links (some alternatives are discussed in [173]). Therefore, we vary this offload percentage to study its impact on performance of the cellular network and D2D links.

As Fig. 3.19 demonstrates, there is a clear increase in cellular network throughput, when offloading is enabled, and the more we offload, the higher is the gain. In consequence, there is also a limit on how many sessions can be offloaded (which is about 30%; based on the simulation scenario). As the figure shows, D2D links perform best, when the offloading percentage is low, and their performance degrades as the number of offloaded traffic sessions grows. This happens primarily due to increased contention between D2D links, but also due to rising noise levels.

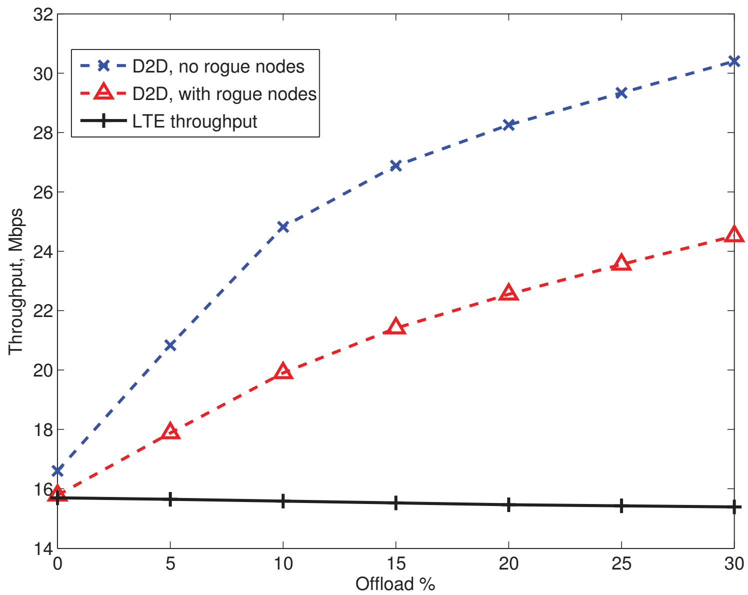


Fig. 3.19: D2D offload throughput [34], [168], [169].

Each WiFi transmission in the deployment (even those whose transmitters are far away from the receiver) contributes to the overall noise level in the WiFi band, decreasing channel quality by a tiny fraction. At some point, when hundreds of such transmissions add up, there is no longer any benefit from offloading additional traffic sessions.

Mentioned effect can be noticed in Fig. 3.20, which confirms that at 30% offloading rate, the energy efficiency almost matches the case, when there is a significant rogue interference in the deployment. Energy efficiency is computed based on the 100 mW circuit power, 200 mW RX and 100 mW + transmit power for TX.

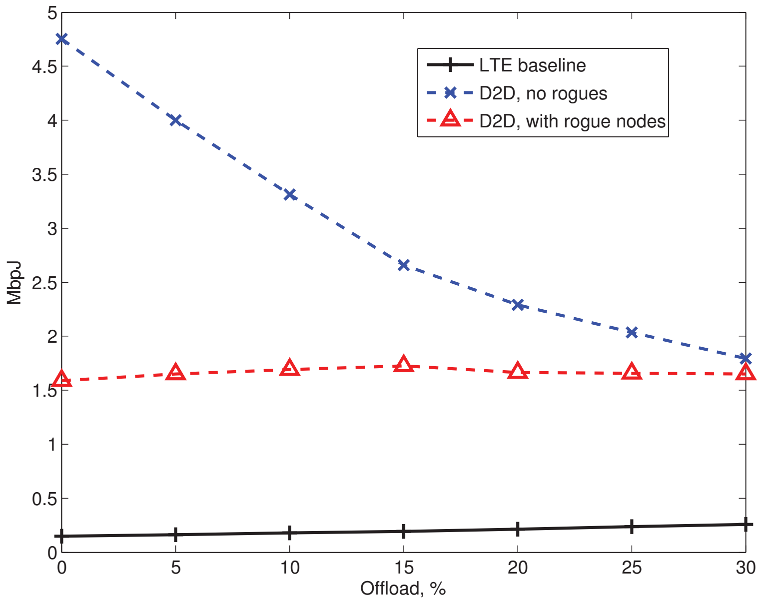


Fig. 3.20: D2D overlay energy efficiency [34], [168], [169].

Surprisingly, once the WiFi band is saturated, additional offloading onto WiFi-Direct links does not notably decrease energy efficiency. This is a consequence of CSMA/CA procedure behavior, which is at the heart of every IEEE 802.11 protocol. With CSMA/CA, the more interference there is, the longer time clients spend in the back-off state, consuming very little energy. By comparison, when the LTE network is heavily loaded (i.e., interfered), end users stream data at very low data rates over excessive periods of time, thus suffering from significant battery drain.

One detrimental side effect of increased offloading onto WiFi-Direct links is the time it takes to get a packet through the MAC layer. As Fig. 3.21 indicates, the MAC delay (i.e., time from the moment a packet enters the MAC layer until it is acknowledged) for D2D links quickly grows beyond that of LTE links as the offloading percentage increases. This process will eventually stall longer links, as they tend to have more competition for channel access. Concluding the obtained results, offloading is not a universal solution for all problems – without proper bounds the overlay network would get overloaded, and the energy efficiency gains will vanish, while the delay would grow excessively high. However, there is a large "sweet spot[7]", where D2D offloading provides significant boosts to (i) capacity, (ii) energy efficiency, and (iii) sometimes even reduces delay [34], [168], [169].

The implementation details of network-assisted WiFi-Direct will very much affect the achievable performance gains from offloading onto D2D – e.g., if the network is allowed

[7] A combination of factors which results in a maximum response for a given amount of effort.

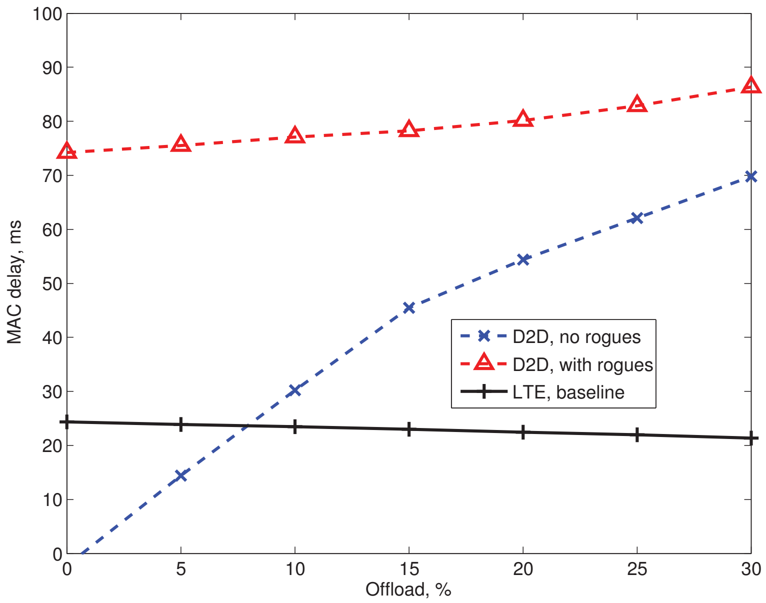


Fig. 3.21: D2D offload MAC delays [34], [168], [169].

to assist with device discovery (as in study), data offloading will be significantly more reliable and resource efficient. But this is only one form of network assistance; there are many other ways, in which the network can assist D2D links to improve service quality and continuity. For example, if the network is given the ability to control which D2D links are established, it could avoid offloading onto D2D links that degrade network and/or user experience. Similarly, if the network can control when certain D2D links transmit, it could potentially establish scheduling zones when groups of non-competing D2D links are allowed to communicate, thus potentially significantly reducing contention and improving throughput and energy efficiency of D2D links (here the reader is referred to works [174], [175]). For sure, advanced power control options also become available when the network assists D2D communications [176].

3.2.3 LTE-Assisted WFD D2D System Implementation

With finished preliminary research [34], [162], [168], [169], [177], we have identified numerous benefits that could become available if a coordinated, network-assisted D2D technology is deployed by network operators. On the other hand, introducing D2D technology within today's network infrastructure poses a number of challenges and requires updates to the current longstanding cellular architecture. Therefore, to conduct a comprehensive study and reveal the practical promises of D2D communications, we have designed a trial development and deployment program.

Our trial was aimed at demonstrating how the direct connectivity paradigm could be seamlessly integrated into a real-world, operator-grade cellular network with minimal modifications and overheads, as well as within a reasonable time frame. Our secondary goal was to quantify gains that could be achieved by a fully-functional, operator-supported D2D system. As a equipment basis for our trial, we have utilized the experimental LTE-A network of Brno University of Technology (BUT), Czech Republic, which supports most of the functionality expected of LTE Release 10 systems. During the implementation phase, we have upgraded the LTE network of BUT with our own implementation of Proximity Services (ProSe) functionality as envisioned by the 3GPP specifications [178], [179]. This has allowed us to perform live D2D integration trials, along with corresponding performance evaluations.

D2D Standardization Activities

The key enabling technologies for D2D communications have been around for years, since practically any IP-ready mobile device is tentatively capable of direct connectivity. However, the development of the necessary supporting standards and user interfaces has extremely lagged behind any developments in related technologies, with the first D2D activity started by 3GPP in 2012 within the framework of ProSe. 3GPP TR 22.803 [178] is known as the initial document to specify what exactly is to be understood by the term "proximity-based services" and D2D naturally fits into this category. However, 3GPP ProSe specifications and associated work items cover, in fact, a much broader area. They address the phenomena in both society and economy that drive the need for proximity-based communications, including such examples as social networking; disaster relief and emergency service operations; advertising; and so on [172], [180]. As a result of this work, the decision was made that ProSe functionality has become a part of future LTE releases.

Consequently, the technical side of providing ProSe mechanisms demanded attention. In particular, a requirement has emerged on establishing proximity in an efficient way without revealing personal user information. Indeed, proactively requesting any content via short-range radio links discloses the type of the desired content, whereas broadcasting content advertisements discloses what is available to share. Either way, users of a proximity-based discovery service, both content providers and consumers, may prefer to remain anonymous or impose their customized policies on a set of targeted peers. With decentralized solutions, such as those offered by WFD, meeting the aforementioned requirements is clearly impossible. This, in turn, has led to research on a potential Evolved Packet Core (EPC)-level discovery procedure, where a 3GPP network would act as a trusted intermediary and implement all of the necessary policies on behalf of users. The report TR 33.833 [181] quantifies specific goals, which have been respectively targeted by 3GPP.

Currently, since the overall vision of how the ProSe function is to be implemented has already taken shape, follow-up work has begun on supporting infrastructure, such as billing [182]. As of 2015, most of the architectural progress on ProSe and D2D communications is summarized in the TS 23.303 document [183]. It is likely, however, that additional amendments will be made when the activities on the technical side of unlicensed LTE commence [184]. Today, some of the related ideas on potential license-assisted communication (RP-140770) and on LTE-based short-range radio within licensed bands [185] have already been documented.

However, aside from their in-house efforts on short-range radio, 3GPP also supports alternative non-3GPP radio technologies, including WFD, for ProSe radio communication. The integration between 3GPP and WiFi solutions has been a long-standing effort, with specifications TS 23.234 [186], TS 23.327 [187], and TS 23.402 [188] outlining how LTE devices that are connected over non-3GPP access technology, could still receive access to all of the 3GPP services. Following this lengthy integration effort, all current ProSe architectures support the use of IEEE 802.11 family, as a link layer for most of the ProSe functions, with the exception of public safety services [183].

Architectural Considerations

Envisioned implementation of the generic D2D system concept offered by the standards has naturally met a number of deployment challenges that made us deviate from the reference solutions. Current architectural considerations of LTE networks preclude us from deploying the network assistance functions in the way that would have been the most "natural" from an engineering standpoint; thus, within the novel implementation introduced in this work, it was necessary to adopt several clever workarounds to develop a workable system with today's technology.

In what follows, the key decisions made in each step of the deployment process are discussed. The experimental cellular network setup installed at the Department of Telecommunications, BUT (see Fig. 3.22) stands for a complete commercial-grade implementation of all the crucial subsystems comprising contemporary 4G mobile networks.

Utilized trial deployment is configured to provide the necessary packet-switched data access services and their derivatives, such as VoIP communications over converged LTE and WiFi radio access infrastructure. The EPC is dimensioned to enable high data rate services with appropriate QoS and QoE provisions, as well as to support up to 100000 concurrently served users. For voice and video calls, the switching capabilities are implemented by employing the high capacity IP Multimedia Subsystem and its related components, for both mobile and fixed access users, as well as for connectivity to external telephone networks and teleconferencing systems. The general goal behind BUT's LTE test network deployment has been achieving the synergy of a complete and customizable experimental mobile network that allows for rapid implementation and prototyping of novel concepts and technologies, such as the D2D communications paradigm discussed at length in this section. We thus effectively used this asset to showcase that the LTE-assisted WFD technology has matured enough for an example implementation in a commercial-grade LTE/WiFi network.

However, several LTE mechanisms expected by the ultimate network-assisted D2D architecture were not available at the time of our early implementation. This included the evolved Serving Mobile Location Centre (eSMLC) server, for which an alternative interface to obtain device location information directly from a Mobile Management Entity (MME) has been developed as a substitute. In addition, the D2D server functionality has been implemented as a virtualized appliance, whereas the final commercial operator-grade

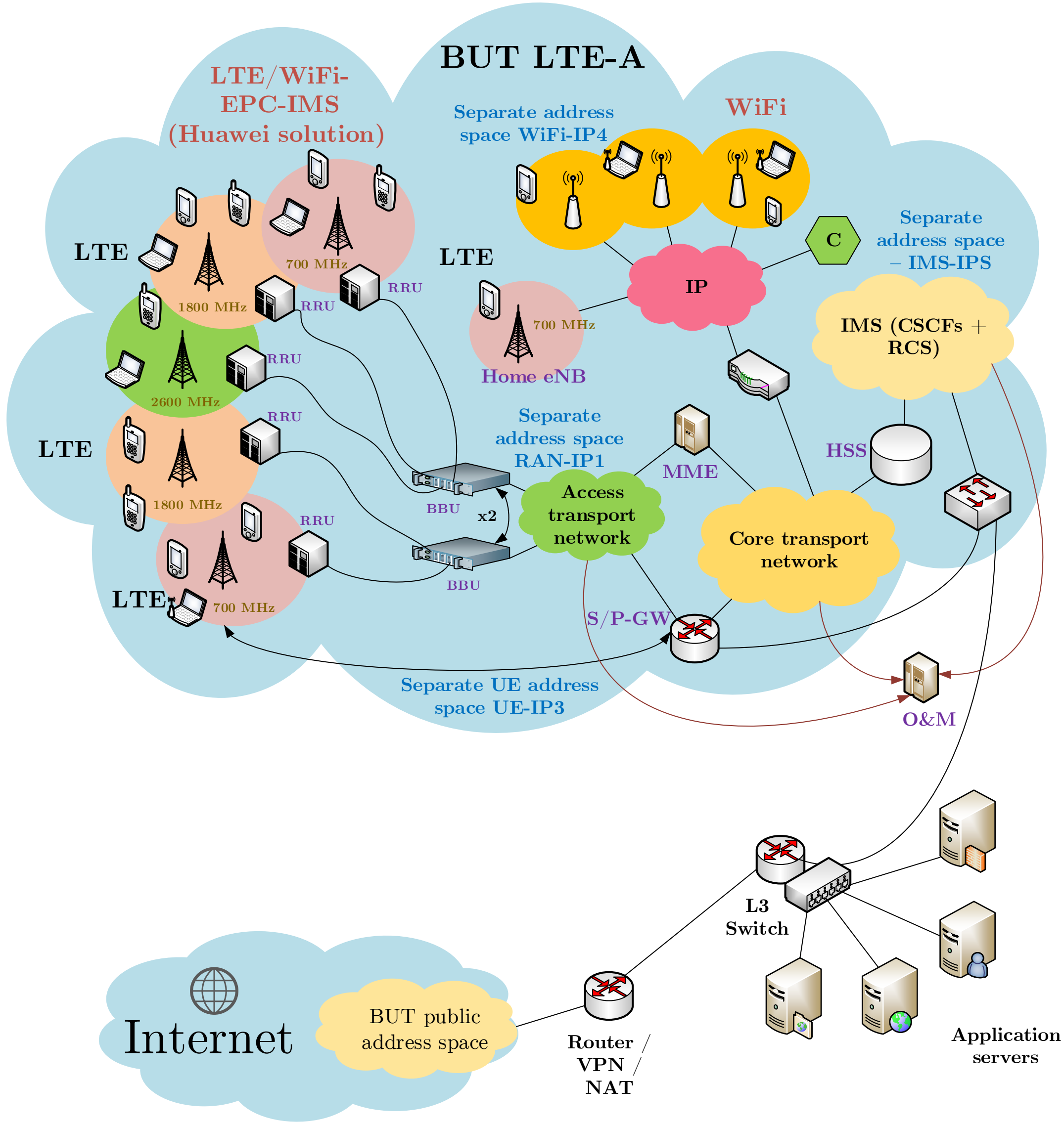


Fig. 3.22: System topology of experimental 4G cellular network deployed at BUT, Czech Republic [34], [189].

implementation should preferably use a more robust technology. Further design choices are explained below [34], [168], [169].

Impact of Radio Access Network on D2D Communications

A radio access network (RAN) is crucial for any kind of service in a mobile network. To this end, RAN is typically required to transport signaling and data. That being said, D2D communications are not particularly demanding with respect to RAN capacity, as D2D messages are only few bytes in size, and ultimately D2D communications reduces the RAN load. The D2D signaling should, however, be prioritized to decrease service response times. Correspondingly, the impact of RAN loading on the observed service times has been measured extensively in performed experiments. Other RAN functionality required for LTE-assisted D2D communications is positioning. Providing user location information is achieved via cooperation between eNBs and other EPC elements, and is described thoroughly at length of following sections.

Notably, neither special configuration nor non-standard service is needed from the RAN side for the D2D system to function. A deployed RAN is part of our test-bed installation. Generally, commercial-grade equipment is used, but the RAN itself is not a part of the radio access subsystem of a mobile network operator. Hence, we have complete control over the RAN loading conditions. Finally, as our RAN solution is deployed as real application, external interference is present.

Providing Unrestricted IP Connectivity

One of the key requirements for any direct user connectivity is the ability to communicate between devices without any intermediary hosts operating at the transport layer or above. Typically, in cellular networks, the associated devices acquire their IP addresses from private ranges (for example, 192.168.0.0/16). As long as a D2D link is established within a single operator's network, this does not impose any constraints. However, the effective firewall policies deployed in the core network, which deny direct access between user devices to enhance security, actually cause difficulties. The original purpose of the aforementioned firewall policies could have been prevention of undesired incoming connections and P2P data transfer between different mobile network users. As a result, they deny any P2P connectivity over cellular networks [190].

For the purposes of our network-assisted D2D trial, we needed to circumvent the firewall by making the D2D server capable to open direct communication paths for selected connections whenever necessary. In our case, implementing such functionality has been fairly straightforward, since the D2D server can reconfigure the firewall on a per-connection basis. In our implementation, the firewall is located inside the Unified Gateway (UGW) entity; logically composed of a Serving Gateway (SGW) and Packet Data Network Gateway (PGW).

Communication between D2D Server and Users

By design, D2D network assistance relies on a network's ability to communicate with those user devices that are engaged in direct connectivity with the network. This inherent ability must be augmented by an efficient means of initiating such communications. For example, the said connectivity could be straightforwardly enabled with a session initiation protocol, but this would require an active radio bearer. Having an active LTE radio bearer for only several packets is naturally not conducive to system efficiency; hence, this is to be avoided. In LTE, there are multiple ways to transfer short messages between a network and those individual users of the network that do not require a dedicated bearer setup, such as non-access stratum (NAS) signaling, which is typically used to set up the bearers themselves.

As a result, the practical deployment of the D2D functionality requires an implementation, where the D2D server would be positioned outside of the system core as a conventional IP service, but with a capability to access certain core network functions (see Fig. 3.23). The full-scale architecture of the envisioned D2D offload system is detailed in Fig. A.2. While this may not be the optimal solution in final commercial deployments, it enabled us to move forward promptly with regard to D2D system implementation. Although the proposed location of the D2D server does not follow the 3GPP guidelines exactly, we believe that our modification does not produce any negative impact with respect to latency, as the connection between the SMLC and the D2D server is implemented via a tunnel over a fiber channel.

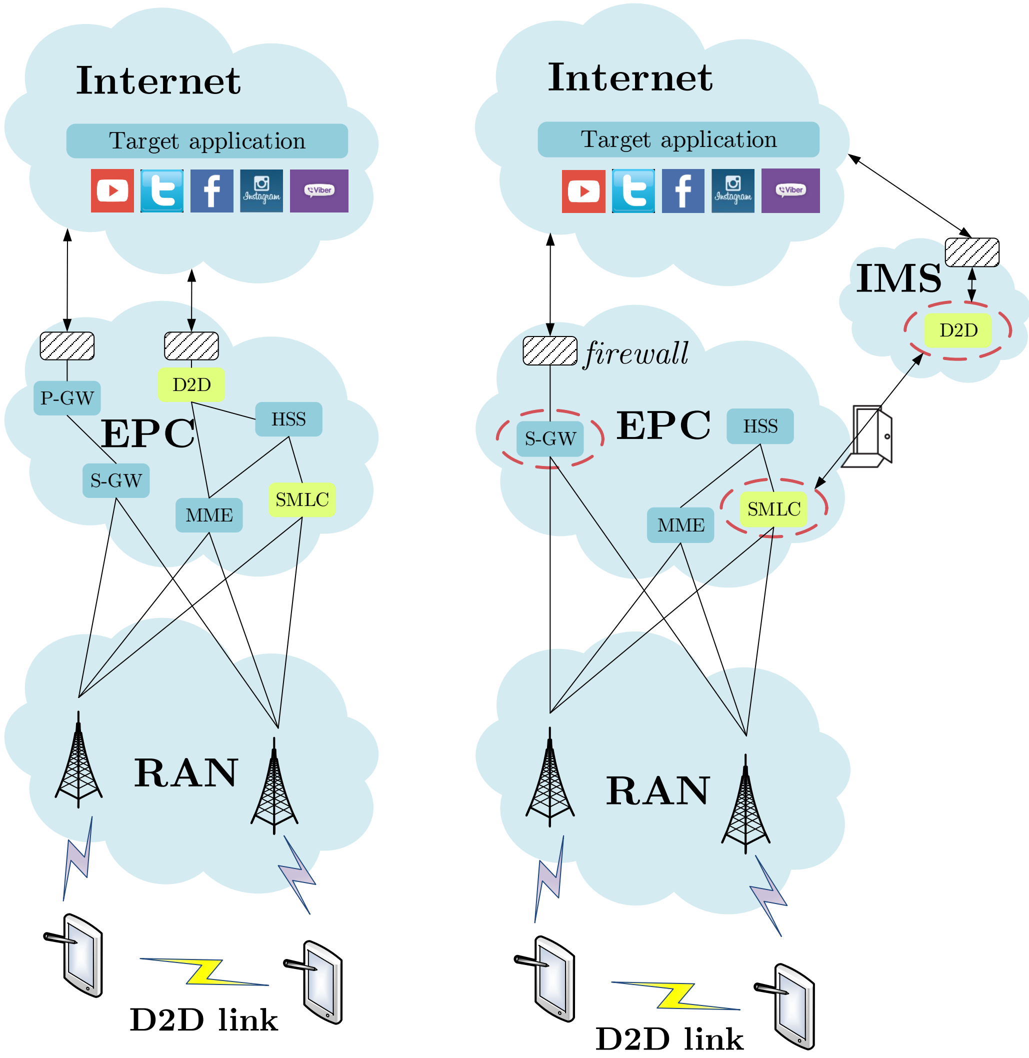


Fig. 3.23: Comparison between (a) hypothetical/standardized and (b) our deployed implementations of D2D system in 4G mobile networks [34].

Integrating Location Services

For the network-assisted direct connectivity to operate efficiently, the D2D server needs regular updates on the current locations of users. In LTE, such information is conventionally aggregated by the eSMLC entity to be then made available for the user devices via Secure User Plane Location (SUPL) bearers. A copy of the location information in question is typically stored inside the MME for its internal usage. Whereas the exact means of how this information is obtained may vary, the general procedure is such that a phone's GPS location will be used if available. Alternatively, the positioning reference symbols within the LTE frame will be used to pinpoint the location of user equipment (UE) through triangulation.

Either way, the coordinates are obtained in line with the standard techniques outlined by 3GPP and are enabled in most modern equipment (post Release 9). As a result, enabling location-based services is not a major challenge in contemporary LTE networks, and most of the time such functionality is already provided by the operators for the mobile devices to use.

In the considered proximal scenario, the D2D server accesses the location information on behalf of the UE, and then draws conclusions on whether other UEs are sufficiently close to initiate direct communication. An example of such decision logic is presented in Fig. 3.24. With the help from location services, the UE can thus power on its radio only when the intended contact is in proximity, hence saving battery and network resources. The specific signaling used in the trial is further discussed in following sections. Naturally, one would need to select the thresholds triggering various decisions, but those are largely hardware-specific and have not been the core subject of this research work.

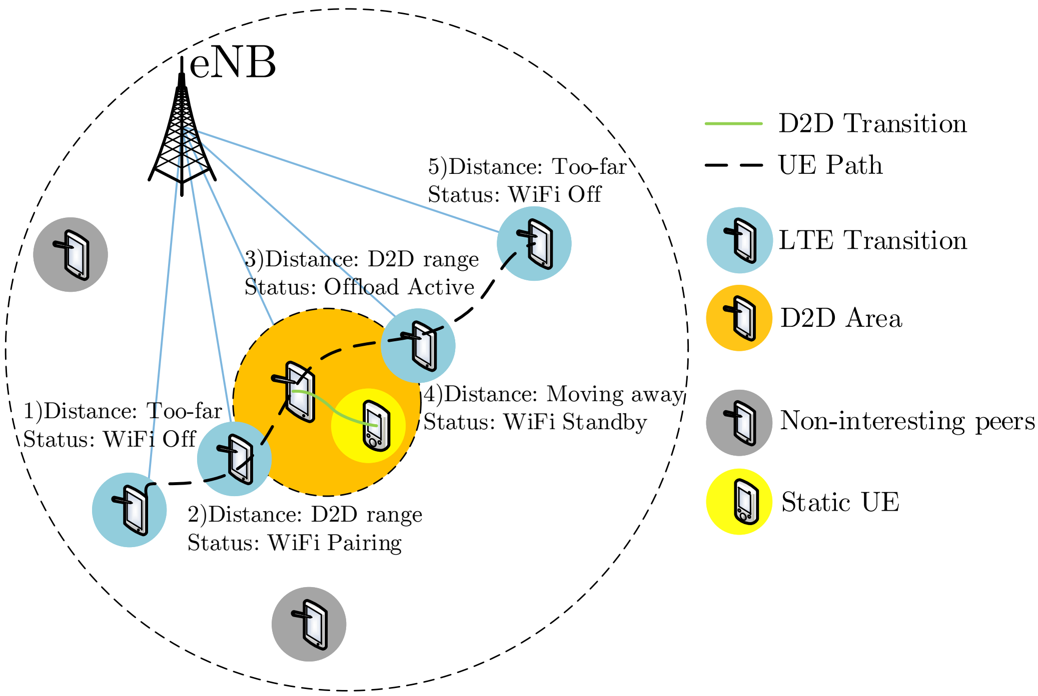


Fig. 3.24: Switching logic between LTE and proximal D2D connections, as mobile UE is moving along its route and meeting static D2D peer [34].

Linking D2D Server and Core Network Components

Recall that the location information is typically made available in LTE only for MME and the UEs themselves. Similarly, the interfaces to control the firewall policies at the UGW are also core-local. In our implementation, we had to create a secure connection to the core to allow the D2D server to communicate with the MME and UGW, as to extract the location information and configure firewall policies via the maintenance interfaces, which is, of course, not the preferred final solution to go with.

In reality, one would require enabling the D2D server to connect to the MME/SMLC and UGW via an efficient and secure application programming interface (API), without exposing the entire management console. Due to the time limitations imposed by the purposes of this trial and to the vendor-specific nature of the firmware, we have left the development of such API for future work.

D2D Connection Control

Efficient control of D2D connectivity between UEs deserves a separate dedicated research, which can be generally split into signaling and executive components. The signaling may be handled by a service that is running as a service on the mobile device, whereas the executive part is essentially integrated into the kernel drivers of the operating system (OS) of the UE.

While implementation of the signaling part as an application is rather trivial for most of today's mobile phones, actually forcing control over WiFi and cellular connections (together with the associated routing table) requires significant modifications to the permission levels of the UE. In practice, for most platforms (Android, the majority of Linux-based systems, and so on), this means employing custom-built firmware for the phone, or obtaining the administrative privileges by virtue of hacks and exploits. For closed platforms, such as iOS and Windows Phone, these solutions are nearly impossible without cooperation from the platform vendors.

Performance Evaluation of Implemented D2D System

The primary goals of intended performance evaluation are as follows:

- Indicating bottlenecks that could potentially hinder the adoption of D2D connectivity in future wireless technologies.
- Establishing appropriate performance bounds and limitations for D2D technology, as well as outlining what services could be most suited for direct communications in contemporary and near-future markets.

To achieve these diverse goals, we follow the measurement procedures as outlined in the remainder of this section.

Measurement Methodology It is important to note that in this work (by contrast to numerous past publications) we are not interested in the performance of the D2D link itself, since that would largely depend on the current channel and user contention levels. In this study, we specificaly concentrate on assessing signaling performance and network assistance logic, as the latter can be reliably measured in our controlled trial environment. On the other hand, such metrics as D2D throughput are extremely difficult to assess conclusively in practice due to the high variability in wireless environments.

Based on the above reasoning, the single most important parameter of D2D signaling is the connection setup time. This latency is crucial, as lengthy connection setup times may delay the transfer of the flow to an alternative radio link, thus affecting other parameters such as energy efficiency and user experience. Due to small message sizes, in the order of a few tens of bytes, other QoS requirements on the D2D signaling are easy to fulfill and can be provided by any access network; therefore, we are not considering these as key performance indicators for this technology. Other aspects of D2D link performance, which are not directly related to mobile network infrastructure, do not affect service setup response times and, as such, are out of the scope of this work. The connection setup time may in turn be decomposed into several components, as described below.

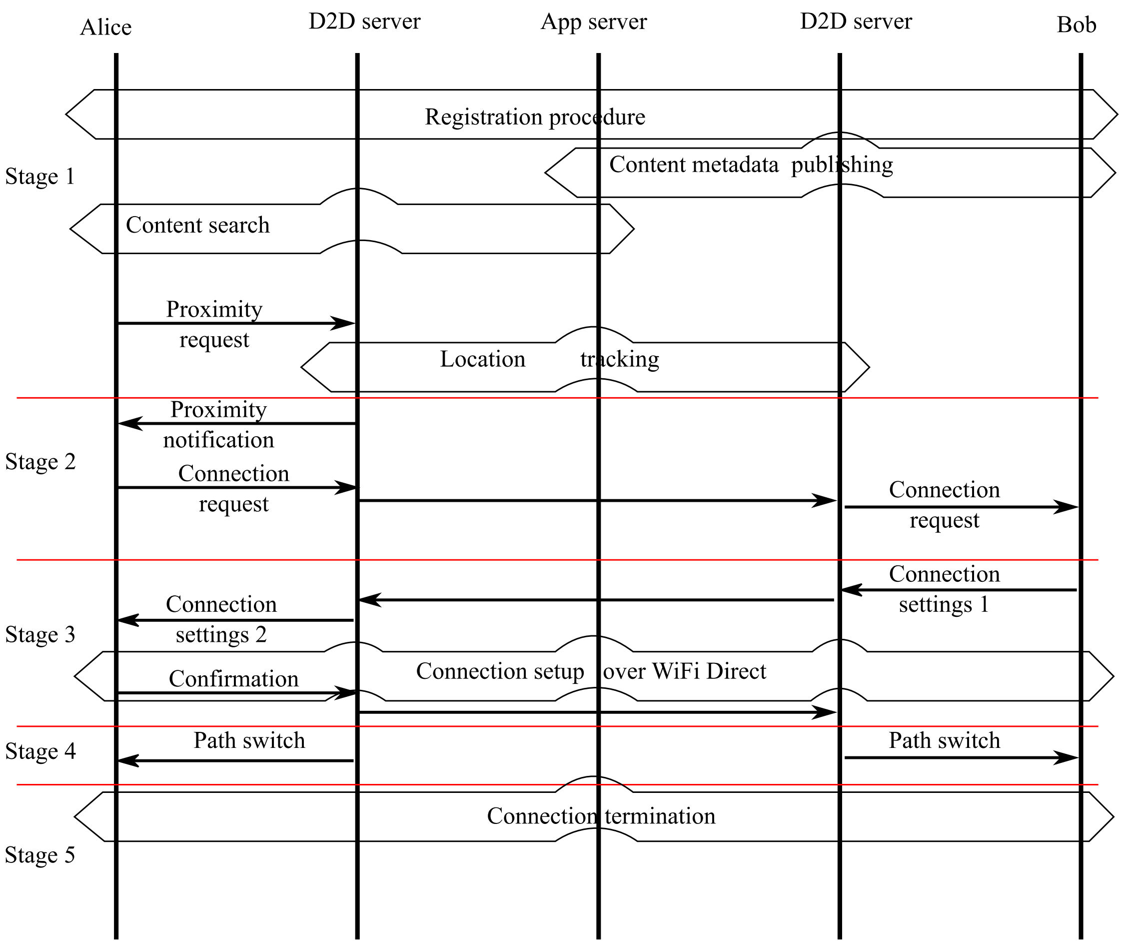


Fig. 3.25: Considered D2D protocol signaling including all five stages required for proximity discovery, D2D link establishment, and termination [34].

First, by looking at the proposed D2D protocol signaling illustrated in Fig. 3.25, we learn that before any WFD connection is actually set up, there are several important actions to be taken from the network side to observe user proximity. Therefore, we decomposed the signaling procedure in question into several distinct stages. In stage 1, the responsiveness of the system is not of particular interest, since the procedures taking effect there are constrained primarily by the human user input.

However, once stage 1 is completed and the proximity is established, the actual D2D signaling is triggered. Ultimately, we have configured for stages 2 (D2D link negotiation), 3 (link setup), and 4 (actual flow switching) to occur as quickly as possible to maximize the effective time during which we can take advantage of the D2D link, especially if the communicating peers are highly mobile. These stages also constitute natural measurement checkpoints, where the resultant system agility would straightforwardly depend on how long it takes to transit from one checkpoint to another. Therefore, we further commit to measure an aggregate latency at each of the above state transitions. To provide the best available accuracy, we have additionally decomposed the considered D2D protocol into individual messages and performed our measurements on a statistically large sample set. The latency has been measured between the client device (laptop Lenovo T430 with the USB LTE modem Huawei E392) and the D2D server (located behind the UGW). Utilizing the modem E392, the laptop has been connected to our experimental BUT LTE network. The distance between the client and the eNodeB has been fixed to 5 meters throughout the entire performance evaluation campaign.

As a measurement tool, Iperf [191] has been employed to assess the maximum throughput of a particular radio access solution. Later, Iperf has also been used to create predefined loading on both uplink and downlink channels to thus emulate specific conditions on a “deployed” network. The client has been configured in the role of a sink (receiving data traffic from the D2D server) and a generator (generating the constant User Datagram Protocol (UDP) data bit stream for Iperf, which runs on the D2D server). The WFD D2D link setup times have been measured between two Sony Xperia ZL phones, running custom Cyanogenmod 10.2 aftermarket firmware. The link setup time has been assessed following the known-channel pre-shared key (PSK) authentication procedure (essentially, employing the WiFi Protected Access II (WPA2) protocol). The WPA2 authentication enables legacy devices (which do not support WFD extensions) to still join the networks initiated by other devices. The measurement for the connection setup time has been done with the *wpa_cli* interface, by monitoring the time between when a new network has been enabled and when a new connection has been completed. A connection was considered completed once the first IP packet was successfully acknowledged.

Numerical Results and Discussion Following the above methodology, the measured values of the LTE network latency have been obtained to compose Table 3.4, which summarizes the estimated delays introduced by various connection setup stages. Here, the stage 3 delay includes Wi-Fi link setup, as discussed further on. The fractional loads on WiFi and LTE networks have been matched. For LTE, our results indicate that if the overall loading on the LTE network does not exceed 90%, the roundtrip times (RTTs) between the client and the D2D server are generally below 30 ms. Hence, cell loads of up to 90% do not have any evident effect on the LTE signaling procedure when compared with the WiFi link setup time. Under higher loads, the WiFi setup time becomes comparable with the LTE latencies, thus making LTE signaling optimization a concern. This is especially critical since offloading is most needed under high loads.

Tab. 3.4: Network latency measurements for different cell loads

Cell and WiFi load	Idle (10 %)	50 %	90 %	99 %
Measured RTT (ms)	18	25	27	60
Stage 2 (ms)	36	50	54	120
Stage 3 (ms)	750+36	850+50	1000+54	1150+120
Stage 4 (ms)	9	13	13	30
Full procedure (ms)	849	988	1148	1480

In the case of 99% load, the network queues have been overfilled; we can assume this particular scenario to be highly relevant for an offloading operation. The resulting LTE RTT values range in the order of half a second, and without the appropriate QoS support in LTE the obtained latency values would dramatically impact the overall performance of the considered D2D technology.

Further, Fig. 3.26 clarifies the delay values for the different types of cell load. Whereas the values remain negligible for up to 90% loading, the "full-buffer" condition yields a major increase in the monitored delay, which becomes hardly acceptable (in the range of seconds). Therefore, we paid close attention to the measurements in the range 91% to 99% of cell loading. In this extreme case, the implementation of QoS on the UE side is crucial to prioritize the D2D signaling messages, see Fig. 3.27.

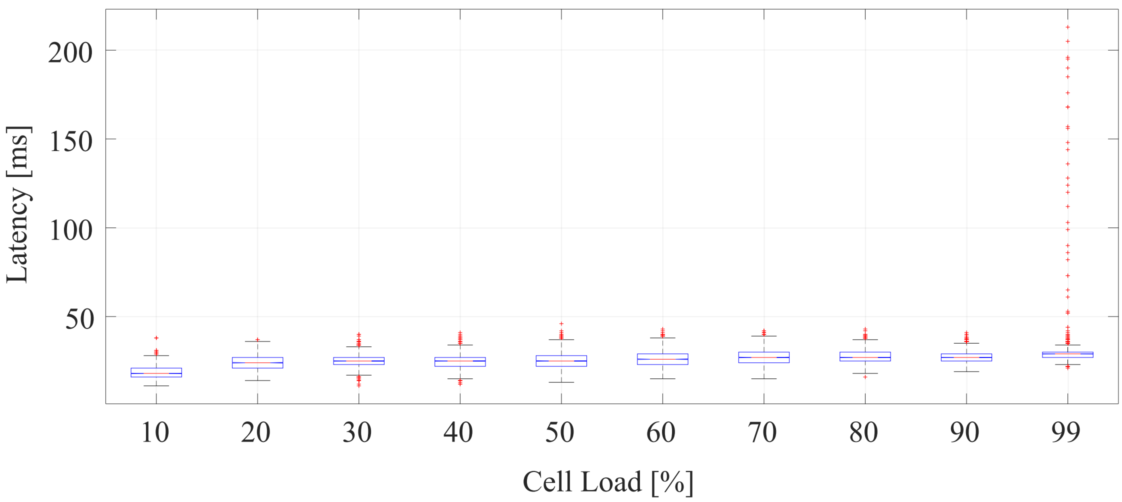


Fig. 3.26: Network latency for alternative LTE cell loads [34].

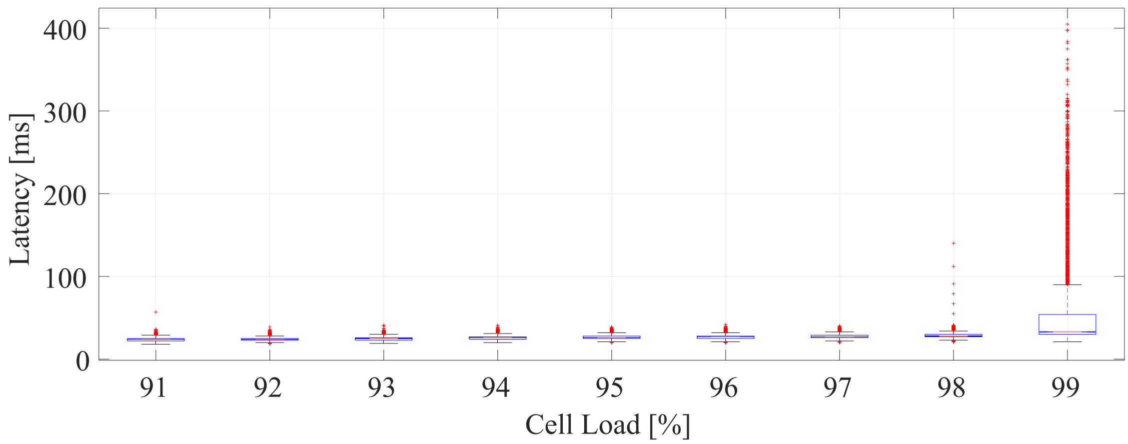


Fig. 3.27: Network latency for extreme LTE cell loads [34].

It is evident that the network conditions remain reasonably stable for up to an extremely loaded state (corresponding to a cell load of 99%). Under extreme loads, the average latencies remain largely acceptable; however, due to the high variance, the perceived quality of user experience suffers significantly. Interestingly, out of all the D2D connection stages, by far the most costly ones are connection negotiation and the actual setup of the link. In practice, those require several RTTs to complete and may add up to several seconds of signaling time in highly congested cells.

Naturally, this necessitates further improvements to how the signaling messages are carried, since the primary goal of D2D is to actually reduce the load on the cellular links; moreover, the longer it takes to perform D2D offloading, the worse the resultant congestion levels will be. It is noteworthy that the D2D-link tear-down procedure at stage 5 is not instant. However, since the direct links are removed only when they are not needed anymore, this tear-down procedure is not as time-critical. Hence, it is not evaluated explicitly by our present study.

Performance Summary

Based on the performance numbers obtained above, one can conclude the following on the current bottlenecks of the LTE-assisted WFD implementation:

- The WFD link setup time could be dramatically shortened by removing the OS-introduced delays. While this does not significantly affect user experience, it does delay the actual start of offloading. Under most conditions, this overhead is nearly constant.
- The D2D connection negotiation stage is the primary bottleneck in an idle LTE system, as it involves multiple RTT cycles to complete, and can grow exceptionally under heavy cell load.
- In a loaded network, any communication with the D2D server may take a considerable amount of time since the signaling traffic shares the same channel with the data traffic due to the absence of dedicated bearer support in the mobile OS API.

- If the users are highly mobile, then their location tracking may become inaccurate, thus resulting in false proximity notifications or late link establishments due to relatively short durations of effective proximity.

At this point, it has to be reiterated that while the conventional performance metrics typically focus on throughput, in this particular case of offloading, the subject of specific interest is signaling procedure, see Fig. 3.28, rather than the gains ultimately attainable by its use – video overview of performed trial is available[8].

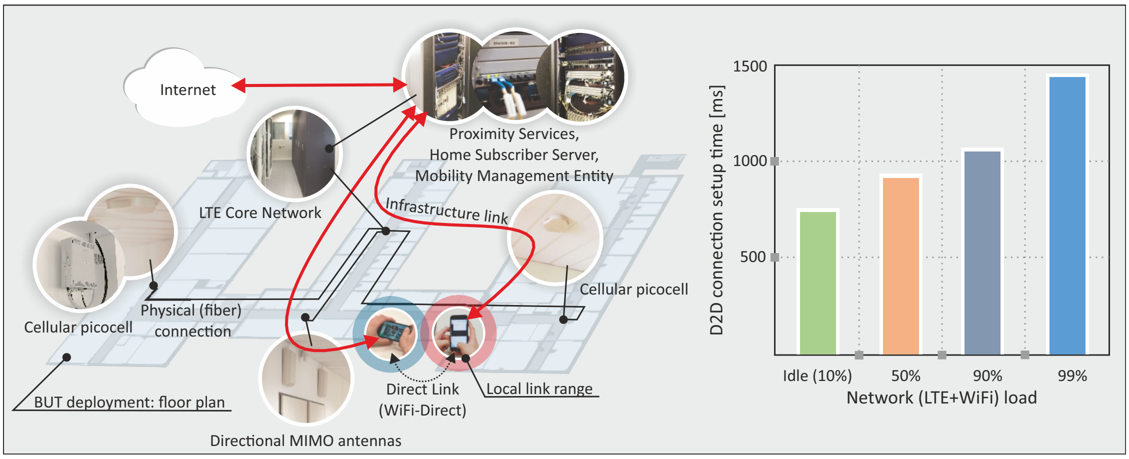


Fig. 3.28: Trial of LTE-assisted WiFi-Direct technology [177].

In summary, as far as future proximity-based services are concerned, we are convinced that it is entirely feasible to utilize our considered network-assisted D2D logic for mobile devices moving at least at pedestrian speeds. Whereas there is some additional delay introduced by network assistance signaling, in almost all cases the connection will be established on time for the users to reliably benefit from it before they come into physical contact, even when walking toward each other.

[8]http://wislab.cz/our-work/lte-assisted-wifi-direct

3.3 Social Trust Communication over Direct Links – Secure D2D Messaging

In today's cellular networks, the central control infrastructure that orchestrates the associated wireless devices is deemed always available. Consequently, given its reliable and ubiquitous presence, cellular network is typically assumed to serve as a trusted authority for security purposes. In proximity-based D2D communication with continuous cellular connectivity, the 3GPP LTE base station is responsible for managing security functions within the network, and most of the corresponding operations can thus be handled over the Public Key Infrastructure (PKI) [192].

On the other hand, for wireless architectures not relying on pre-existing network infrastructure [193], [194], communication and security functions are distributed across users. If simultaneous use of more than one radio interface is allowed, a variety of new attacks [195], [196] become possible, which advocates the use of PKI whenever available.

The key requirements for hybrid systems without permanent centralized management can be identified as follows [197]: (i) a reliable connection establishment control algorithm; (ii) an adaptive mechanism for rapid response to network topology changes or node failures; (iii) a multi-hop communication possibility; and (iv) an algorithm enabling continuous secure connectivity even when the cellular base station is not accessible.

3.3.1 Implementing the Proposed D2D-Centric Information Security Solution

In this research work, we assume that a remote server in the core network or in the Internet operates as a trusted authority (TA) for the application users, i.e., the server certificate PK_{TR}, N_{TR} is distributed along with the application though the repository as it is shown in Fig. 3.29. Importantly, all the cellular base stations of the operator are connected to this server and may concurrently distribute the coalition certificates signed by the TA, that is, PK_c and SK_c. Alternatively, those certificates may be distributed directly via a cellular link from the TA [28], [29].

As mentioned previously, all the communicating devices have a pre-generated set of parameters: ID_i is a unique identifier assigned for the i^{th} device using a particular application and PK_{TR} is a trusted authority certificate in order to verify the validity of the coalition and other devices (users). Additionally, each of the D2D partners would obtain a PK_c in relation to a specific coalition and then generate the PK_i – its own public key, the secret key SK_i, and a certificate share $cert_i$ signed by the SK_c. Here, we define $cert_i$ as a primitive for the Shamir's secret sharing scheme, i.e., the RSA-based algorithm for the sake of simplicity. These parameters are, in turn, required for the appropriate protocol operation in our target D2D scenario [198].

Initially, we require that all of the devices have a reliable cellular connection to the TA and thus we outline the case for a new *blank* device to join a coalition of *light* devices. Importantly, the actual cellular connection status of the joining device is not important

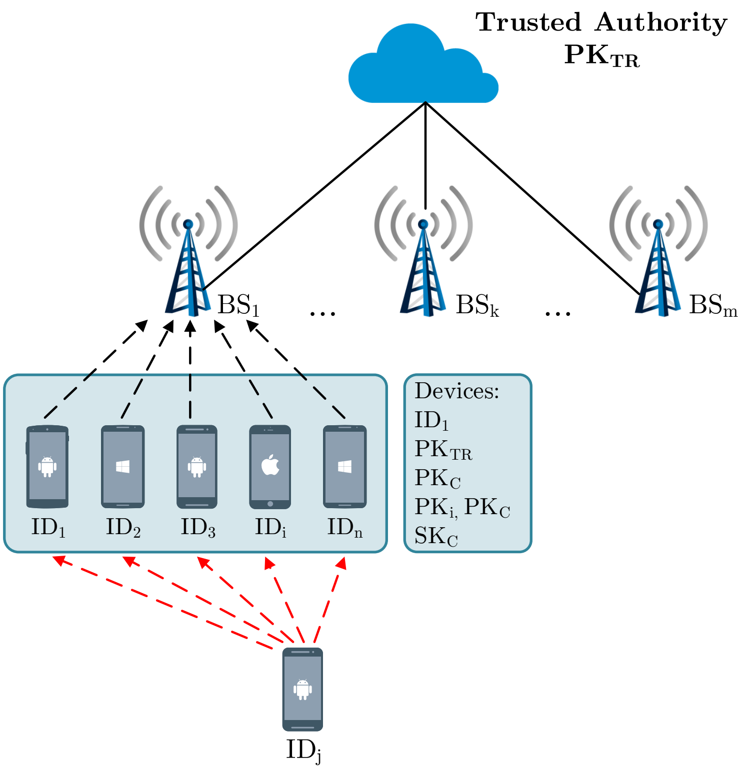


Fig. 3.29: Network topology from the coalition's point of view [198].

for the proposed protocol operation. However, as we assume the existence of two protocol stacks for different connectivity states (ad hoc for WiFi and infrastructure for LTE), there is a need to consider these in details. For the infrastructure case, certificate distribution is a well-known PKI task, i.e., a new device is requesting the base station directly to join the target coalition. The base station then has to redistribute the new certificates for all the communicating devices belonging to this coalition.

On the other hand, the cellular connection may be unavailable for (some of) the devices in the coalition when a new device requests to join it – this is the case when a *blank* device is joining the *dark* group. Accordingly, the joining device is initialized by generating the PK_i and SK_i. Based on the fact that none of the devices have their connection to the TA at the moment, we rely on the coalition itself when admitting the additional device. This, in turn, requires a *preset* parameter included into the PK_c certificate, which is a threshold value of k characterizing the number of devices in the target coalition that have a right to allow the new device to join it. This threshold value is chosen at the stage of coalition initialization and may vary based on the number of devices n and/or other factors; thereby a new certificate would be obtained for the joining user that is indistinguishable for the base station.

From the mathematical point of view, this procedure may be implemented at the base station side as follows [198]:

$$\begin{aligned} f(x) &= a_{k-1}x^{k-1} + a_{k-2}x^{k-2} + ... + a_1 x + SK_c, \\ f(0) &= SK_c, \end{aligned} \tag{3.1}$$

where a_i is the generated polynomial indexes, k is the preset threshold value, x is the unique device identifier ID_i, and SK_c is the coalition secret generated for the secure group. Again, for the infrastructure case, the procedure in question is fairly straightforward, but in the distributed scenario the grouped devices should construct a secret for the new user without the cellular connectivity and not disclosing this secret to anyone. For both of the above cases, the certificate component for the j^{th} device is calculated as [28], [29], [198]:

$$cert_j = \overline{PK_j}^{f(0)} mod\, N_c, \tag{3.2}$$

where $\overline{PK_j}$ is generated by the device with additional salt s_j: $(PK_j + s_j)$, $f(0)$ is the coalition secret obtained with (3.1), which can be either recovered or used at the base station itself, and N_c is generated at the coalition initialization stage as well.

In the case when the coalition is losing the cellular connection (that is, turns *dark*) and a new j^{th} device is willing to join it, we should consider a more complicated distributed protocol operation. If at least k devices have agreed to let the new device in, then a Lagrange polynomial sequence [199] is employed by allowing one to obtain the value of the function at any point $f(ID_j)$. Using the equation (3.1) in the Shamir's secret sharing scheme, $f(ID_i)$ can be calculated as:

$$f(ID_j) = \sum_{i=0}^{k} f(ID_i) l_i(ID_j), \tag{3.3}$$

where k is the threshold value and l_i is obtained as [198]:

$$l_i(ID_j) = \prod_{\substack{0 \le m \le k \\ m \ne i}} \frac{ID_j - ID_m}{ID_i - ID_m} mod\, \varphi(N_c), \tag{3.4}$$

where devices obtain their shares utilizing the standard Shamir's mechanism and φ is the Euler's formula, given that we make our computations in the modular arithmetic.

Importantly, parts of the equation (3.3) are calculated individually at the device side and it is not allowed to distribute/share these between the devices due to the fact that their own secrets are involved into the generation process, whereas the IDs are publicly available. The required protocol steps are as follows [198]:

1. The joining j^{th} device is sending its request along with its ID_j to the first one of the devices that has agreed to admit the former into the coalition.
2. The device with ID_1 is calculating its part based on (3.3) and adds its salt to the result $\overline{f(ID_i)} = f(ID_i) l_i(ID_j) + s_i$, where s_i is stored in memory.
3. The first device is then sending its result to the next device.
4. Steps 2 and 3 are repeated for all of the k devices.
5. The k^{th} device is sending the final sum back to the joining j_{th} device, which then adds its salt s_j to the equation and sends it to the first device.
6. All of the k devices are excluding their salts one by one similarly to the salt adding procedure.
7. The j^{th} device is excluding its salt an by doing so obtains its needed secret $f(ID_j)$.

The following protocol step is to generate the certificate for the newly joining device. For the infrastructure case, it can be obtained by using the equation (3.2). In the distributed scenario, k devices can recover $f(0)$ by grouping together as [198]:

$$\begin{aligned} cert_j &= PK_j^{SK_c} mod\, N_c = \\ &= PK_j^{f(0)} mod\, N_c = \\ &= \prod_{i=0}^{k} PK_i^{f(ID_i)} mod\, N_c, \end{aligned} \tag{3.5}$$

which should be calculated similarly to (3.1).

Further, we need to consider the situation when the device is leaving its coalition based on e.g., weak proximity. The respective decision may be made by the group or by the device itself. For the infrastructure case, this action is nearly trivial, whereas for the distributed scenario the respective operation has been shown previously. Importantly, the main challenge here is still rooted into the key re-generation process for the updated *dark* group when excluding the j^{th} device. Note that SK_c and PK_c should be kept unchanged while new keys are re-generated and re-distributed for the updated coalition. Here, it is essential to follow the rule: the devices reaching cellular coverage again should be verified for their coalition membership. In addition, as it has been mentioned before, SK_c must not be recovered by any of the communicating devices. Therefore, we have to re-evaluate $f(ID_i)$ while keeping the original SK_c, which can be calculated as [198]:

$$f(ID_i) = b_{k-1}x^{k-1} + ... + b_1 x + SK_c, \tag{3.6}$$

where indexes $b_{k-1} = a_{k-1} + \Delta_{k-1}$ and Δ_i may be generated by one of the trusted devices in the coalition. Accordingly, we can derive new keys for each user in the new group and then re-generate the certificates for all except the rogue device:

$$\begin{gathered} f(ID_i) = a_{k-1}x^{k-1} + \Delta_{k-1}x^{k-1} + ... + a_1 x + \\ + \Delta_1 x + SK_c = f(0) + \Delta_{k-1}x^{k-1} + ... + \Delta_1 x. \end{gathered} \tag{3.7}$$

Finally, it should be noted that if a new device (or a group of the devices) acquires its new key, then it is not required to specify the source – it can be obtained directly from other coalition and does not depend on the connectivity state. However, this solution potentially opens door to an important security challenge: if there are k malicious users, they can form their own group and exclude other devices one by one [198]. However, in this work, we consider this situation unlikely and leave its consideration to our future activities. In summary, we arrive at a point of the complete mathematical model for the proposed D2D-centric IS protocol, and hence we can now proceed with outlining the potential scenarios for secure proximity-based communication enabled by it.

3.3.2 Utilized 3GPP LTE-A Deployment

In order to conclusively trial the proposed theoretical security-centric framework for D2D connectivity, which was recently outlined in our previous research works [28], [29],[30], [198], we aim to develop a prototype application within the most widely used Android platform. The constructed application combines features of a secure messenger based on the proposed information security primitives.

Detailed prototype was developed within the live 3GPP LTE deployment (see Fig. 3.30), which is located at Brno University of Technology (LTE), Czech Republic. The subject LTE core is a fully-operational cellular infrastructure, while the full LTE testbed is utilized for the purposes of research and education. The described experimental 3GPP LTE-A represents a complete commercial-grade implementation of all the crucial subsystems composing contemporary fourth-generation mobile networks. The RAN comprises two eNBs and one Home eNodeB. The indoor eNodeBs are divided into two components: (i) the baseband unit (BBU) and (ii) the remote radio unit (RRU). As a eNB unit, Huawei DBS3900 (an indoor macro base station) is utilized. It features (i) a BBU3900 (management logic for eNodeB e.g., mobility management and modulation techniques in base band), and (ii) the RRU (modulation of used frequency) [200].

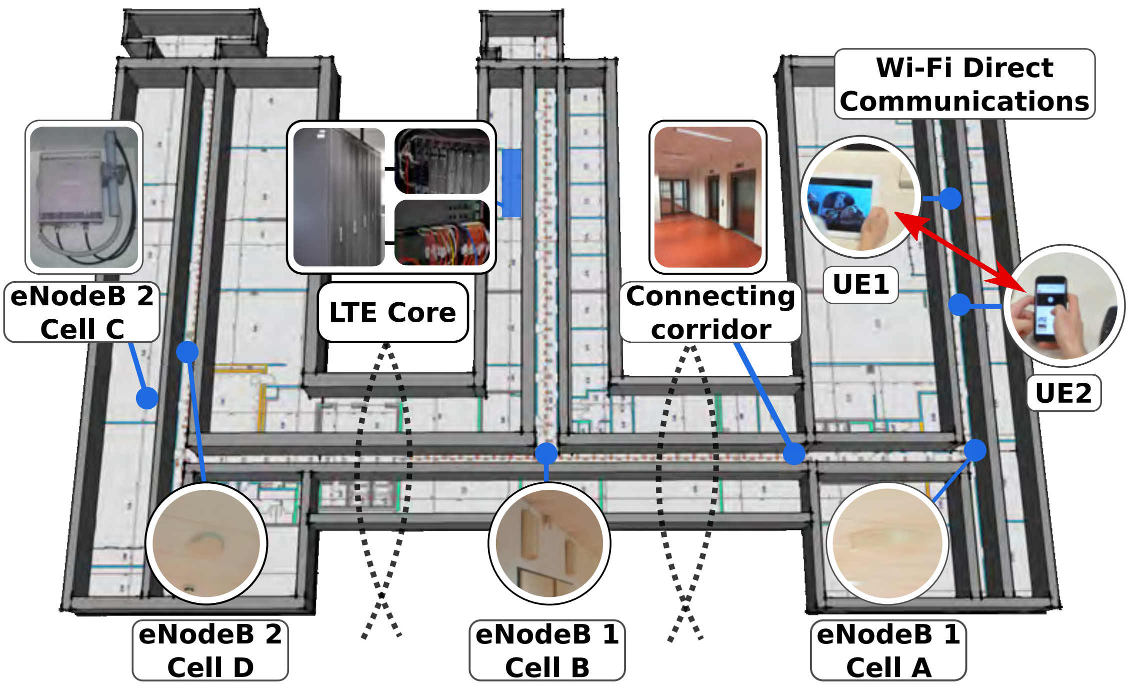


Fig. 3.30: Utilized 3GPP LTE deployment: structure and main modules [200].

In more detail, the eNodeB 1 controls two cells (Cell A and Cell B) operating in the band 17 (originally, the AT&T band in US, 700 MHz). The eNodeB 2 manages three cells (sectors) working on separate frequencies 700 MHz, 2600 MHz (these two are indoor pico-cells), and outdoor 1800 MHz. Next, the WiFi access points (APs) are incorporated together with the LTE cells as part of the integrated network. The APs operate in the ISM bands (2.4 GHz and 5 GHz) and provide with a possibility to utilize packet-switched data services, such as VoIP or VoLTE. For the purposes of testing the emerging technologies, the evolved packet core (EPC) enables access to the RAN part of the LTE network for up to 100,000 terminals (end-users).

Following the recommendations released by the Czech telecommunication office, the TX power for indoor cells is set to 1W (30 dBm) and according to this setting, the available data rates are up to 33 Mbps in the downlink and up to 13 Mbps in the uplink channel. On top of that, the QoS and QoE techniques are implemented for the served terminals. While working on intended trial setup, several modiffications had to be made to the given LTE network – primarily regarding the firewall policies and default configuration of the IMS component. As initial step, we developed and implemented an additional server (physically located in the IMS), which provides the IP-based data communications between the user terminals. Moreover, said server is responsible for (i) the security certificate generation and (ii) the distribution of generated certificates (to offer a possibility of secure data transmission over the mentioned RAN parts of the system, the WiFi and the LTE RANs) [200].

3.3.3 Modifying D2D-Specific Modules

Having unrestricted access to (re)configure the LTE-A network setup, we were able to enable direct connectivity between the devices connected to the RAN part of said cellular network. The various communication technologies (i.e., LTE and WiFi) were utilized jointly without the need for implementation of e.g, separate infrastructure hot-spots. In commercial LTE systems, direct communications between the devices within the RAN is limited by the telecommunication operators. This leads us to the situation when the connected devices can establish their data transmission sessions – even if they are not inside the cellular network coverage.

Importantly, when the user devices are not under the network coverage i.e., the managing entity is not available, it makes the establishment of secure connections complicated. In the modern wireless networks, the IPv4 protocol is used commonly and each connected device possesses a unique IP address for the purposes of its data connectivity. This address is provided by the network (cellular infrastructure) and in most situations is dynamic over time. In case of out-of-coverage communications, new policies and routing protocols should be constructed and implemented, since the default firewall configurations in the deployed LTE networks may restrict the possibility to establish direct access from one device to another. As a result, this might limit the potential opportunities provided by the D2D technology. In connection to the above, we have implemented a new set of firewall policies, which allow for direct communications between the connected cellular network users and the mentioned server (located in the IMS), see Fig. 3.31.

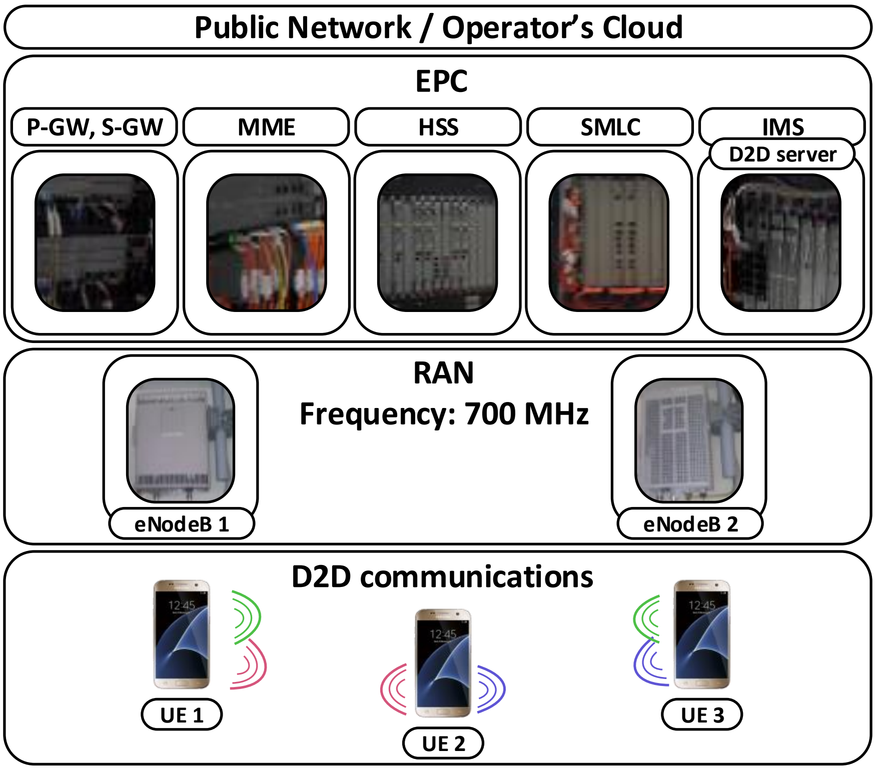


Fig. 3.31: Prototype implementation of a D2D system [200].

3.3.4 Implementing a Secure D2D Framework

The considered D2D system is built upon the advanced security protocols described in [201]. It is intended to be managed by the server operating inside the LTE infrastructure as well as previously described in our past work [30]. To this end, the mobile users may establish and utilize a direct link only if they have a reliable connection to the D2D server that is responsible for the key and connection management [202].

In the networks of today, the PKI within the operator's network is conventionally responsible for the orchestration of the secure communications [192]. However, this technology can only be utilized while having a reliable connection to the infrastructure network and thus many applications cannot be enabled if at least one user leaves the network coverage. The necessary step to maintain the direct connectivity operational is to employ the distributed solutions [203]. They bring along completely new information security challenges related to distributed discovery, authentication, trust, and privacy maintenance, which are traditionally handled by the network operator.

Contemporary systems do not provide efficient enablers for cellular-assisted distributed mobile networking if there is no connection to the server. The real-world topology dynamics and unpredictable changes in trust relationships between the users should thus be tracked back and reported to the network as soon as any of the involved users reach cellular coverage. This is why existing solutions related to the conventional ad-hoc networks are not applicable in the D2D context, as it was demonstrated by our preliminary work in [198]. In what follows, we focus on two main operating modes of the proposed protocol suite: (i) reliable and (ii) unreliable cellular connectivity.

We concentrate on typical cellular-assisted secure D2D group functioning and the corresponding operating states are summarized in Table 3.5. The developed solution builds on top of the 3GPP model and allows to support communications in the situations with no stable cellular connectivity. Importantly, device discovery is assumed to be handled by the cellular service. Therefore, we consider that the cellular system serves as the trusted certificate authority (CA) for the devices involved into proximity-based communications. Each of them has a unique ID and a certificate signed by the CA whenever this device associates with the cellular network initially.

Tab. 3.5: Modes of D2D system operation and our proposed procedures

States	Not in coalition	In coalition
Not in coverage	① Join	② Vote; Leave
In coverage	③ Initialize; Join	④ Initialize; Vote; Leave

Mentioned certificate is utilized for secure group establishment by means of the user validation. The only procedure of our proposed framework that requires stable connectivity to the server is secure group (coalition) initialization. First, the involved mobile devices receive their certificates with the corresponding secret and public keys. Further, this set is utilized to establish secure direct communications with each other. When one of the users is willing to create a secure group with its neighbor, a corresponding request containing the IDs of the future group participants is delivered to the corresponding server in the network. A polling procedure is then triggered by the CA to ensure that the subject users are willing to join the group. After a confirmation has been received, the CA generates a group certificate and a group secret based on the Lagrange polynomials technique, as it is detailed in [198]. After these initial steps, secure direct communications may continue over any conventional IP network.

We emphasize that in the cases of unreliable cellular connection, secure associations inside the group enable D2D communications to be fully operational. Accordingly, the clients do not transfer their data through the server but instead communicate directly. Further, in our proposed framework, the D2D users in the coalition may take advantage of community-oriented voting whenever it is required to include another client into the group or to exclude an existing user from it. The client devices may hence execute a voting procedure in two distinct cases: when all of them have a connection to the infrastructure and thus to the CA or, otherwise, when at least one of them does not have it.

If a cellular connection is available, the operation of joining or leaving the secure group will be regulated by the server. According to the voting results that involve the existing users, the server generates and distributes new group certificates for the modified coalition. Conversely, in case when the infrastructure is inaccessible to at least a certain share of the devices, these clients may vote inside their coalition directly. Such an operation mode might be enabled by means of indirect group secret reconstruction based on a preset threshold value that reflects the required number of users to be grouped together while recovering the secret. Finally, the members of thus updated coalition could recreate a new share to include another device or use their shares to exclude an unwanted user.

Obviously, share recovery coupled with a polling mechanism needs extra computing energy as well as additional exchange in signaling messages as compared to the conventional infrastructure-based operation. On the other hand, the proposed framework offers higher QoS and connectivity experience for the group members. In the following section, we introduce our designed framework and focus on the proposed protocol details [200].

3.3.5 Considered Scenario for Secure D2D

Our prototype implementation of socially-aware D2D setup is detailed in this section. We additionally discuss the proposed framework operation that is also supported by the summary live-trial video in [204]. Within this trial implementation, we have deployed a Linux-based server running a Python service into the 3GPP LTE network with a D2D server, see Fig. 3.32. In this sense, the virtual D2D server is acting as the CA in addition to managing the authentication and the logical IP association procedures.

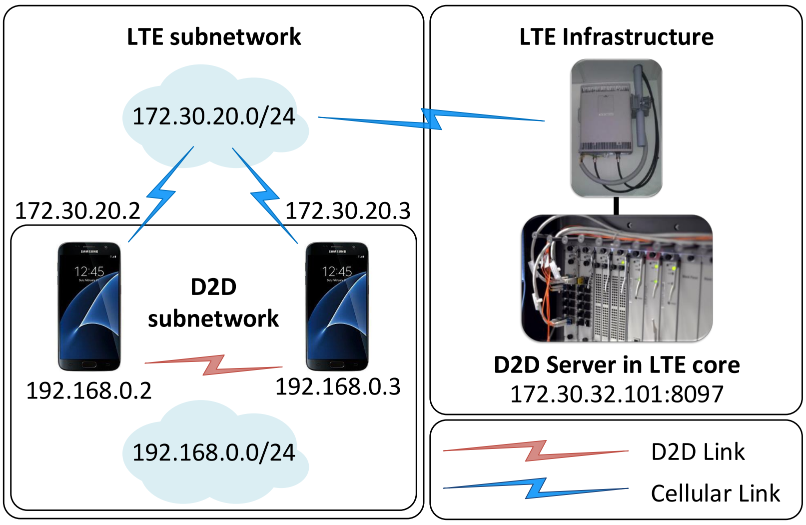


Fig. 3.32: Target scenario for secure D2D communications [200].

The Easy-RSA coupled with the OpenVPN tools were utilized for generating and updating the certificates[9]. A characteristic scenario for the use of our developed prototype is described in what follows.

[9]We employed four Samsung Galaxy S4 phones running non-rooted firmware version 4.4.2 for the purposes of this demo.

Target Application Setup

In our example, three out of four devices are connected to the cellular network. Their users are launching the application that in its turn is generating initial public and secret keys to enable preliminary secure communications. The CA certificate is embedded into the application. Further, each of the devices establishes a connection to the CA via an LTE link using the TCP sockets, where all the initial signaling is signed by the CA's public key. Next, the user's public key is sent to the CA and associated with the user's unique ID Username@PublicIP. Here, PublicIP stands for the IP allocated to the mobile device within the cellular network. Further, the CA generates a certificate for each user and signs it with the root certificate. The server also delivers user certificates and secrets to the corresponding owners, while the public keys are forwarded to other users upon request. As a result, direct CA connectivity on top of the cellular network becomes feasible.

Coalition Initialization

The second phase corresponds to the coalition creation (see Table 3.5). In order to successfully execute the initialization phase, the server requires the knowledge of the clients in proximity that are willing to connect. This information may be based on geolocation, sensing the environment, or cellular assistance techniques. Assume that one out of three clients is interested in creating a secure coalition. Accordingly, this user device sends a request to the server with regards to its proximate clients and receives a reply with their IDs. The initiating user can then select which of these potential partners will be invited into the future coalition. After the users are chosen, the initiating device sends this list back to the server.

Further, polling / voting procedure is triggered at the server side, when each of the client devices from the list is prompted as to whether it is willing to join the coalition. The responses are reported back to the server, which is expecting the replies within a given period of time in order to provide operational consistency. If the reply is not received on time, it is treated as negative. In essence, a group secret is generated based on the Lagrange polynomial sequence [205], and a threshold value for adding and removing users to / from the group is set according to the security policy of the operator/user, whereas each user certificate is being signed by the secure group certificate. User certificates are updated on the user side over a secure infrastructure connection.

Voting in Existing Coalition

Reliable Infrastructure connection As the next phase, we discuss the user adding in case of a reliable connection to the server, which may occur in case ④. Here, one of the user devices included into the existing coalition is requesting the server to add a device that is not a part of it yet. The request contains the group name and the ID of the device to be included. The CA is further triggering the polling procedure and collects the replies. If the reply is not received within the preset time period – the answer is assumed as negative. After the decision is reached and in case it is positive, the certificates are redistributed correspondingly as well as the coalition secret is updated. Exclusion of a user is performed similarly. Additionally, a user can leave the coalition on its own, by removing the group certificate and/or reporting on this fact to the server.

Unreliable Infrastructure connection Compared to the infrastructure case, adding and removing users without such a connection becomes more complicated task, i.e. in modes ① and ③. At first, users are obliged to execute the routing protocol allowing message exchange via ad hoc-like network. Having a knowledge, that users are already in proximity, i.e. in the same subnetwork, protocol obliges their devices to re-associate their IP addresses utilized when connected to the server. Regrettably, Android platform does not natively support such functionality [206]. Therefore, we have reimplemented it using *our own solution*: given that the unique device ID includes the IP address together with the user name, where the former is used in the cellular network and cannot be changed manually by the user, the application can only interact with the IP on the WiFi interface.

For example, in case the distributed network resides in a conventional LAN subnet of 192.168.0.0/24, we naturally limit the maximum size of our secure coalition to 254 users (may be changed for IPv6 networks). This is achieved by the replacing one octet from the LTE to WiFi interface [10].

When the simple distributed routing is established, we had an opportunity to focus on the security protocol implementation in cases of unreliable cellular connectivity. Further, we briefly describe the coalition joining procedure in case when the CA is unreachable. Our only requirement for supporting this case is for any new user to reside in the same physical wireless network as the rest of the existing users in the coalition. If this requirement is satisfied, we can imply that all of the coalition users are in proximity and can communicate with each other. Therefore, a new user should distribute its public key (previously signed by the CA) among all the coalition partners at first.

If the joining device creditability was successful, the user may be invited to the coalition by local polling, triggering by one of the trusted devices in coalition. The inviting device is collecting responses from the rest of the participants. If the number of acceptance replies is higher than the threshold value, the group launches the joining protocol by means of new share generation. In essence, it is a modified secret recovery scheme based on a Lagrange polynomial sequence, i.e., if k out of n devices group together, they can indirectly reconstruct the polynomial and obtain another *point* on the curve for the newly-joining user.

The user execution is performed in the similar manner, i.e., a set of users may group together claiming to exclude one from the coalition. They cannot affect on the share of unwanted user but regenerate coefficients for their shares, i.e., changing the behavior of the polynomial equivalently between all the users to be kept and saving the original secret

[10] For instance, a device with the IP 172.30.20.5 on the LTE interface may suffer from unavailable connectivity to the server and thus the WiFi IP would be set to 192.168.0.5. By doing so, the users in the coalition are able to keep their connection running even without the centralized management.

of the group. Importantly, when new user is included to and excluded from the secure group, the *actual* participants store the chain of the coalition modifications that is signed and redistributed after each event.

Based on this chain, the server can later receive a complete and trustworthy update on the events that have occurred to the coalition while it has remained unreachable. The main idea here is to keep track of the certificate updates on the group side and, for example, the latest version has higher trust value. Finally, any device can leave the coalition at any moment of time by removing it's own share.

Usability Evaluation of Developed Prototype

Within this section, we analyze how usable the proposed socially-aware D2D system could be if we would increase the provided level of strong cryptography for our proof-of-concept (PoC) implementation. Information security specialists are now recommending the use of at least 1024 bits key size and this is taken as the main parameter of our evaluation here [207], [208]. This size is also expected to grow further for up to 3072 bits by 2030. Therefore, we aim to analyze the effects of such an increase on our proposed solution. We note that the most important factor for the mobile device users is the application response time i.e., the delay. Hence, we consider the certificates, keys, and shares generation time observed by the user for both cases of reliable and unreliable connectivity to the infrastructure.

Based on the protocol operation model and prior to actual direct communications, the users have to obtain a certificate containing a secret and a public key. On the one hand, it is recommended to be handled by the corresponding server inside the cellular infrastructure and delivered securely. On the other hand, this pair of keys could be generated at the user side if the network connection does not provide with the required reliability. Accordingly, Fig. 3.33 offers a summary of the corresponding execution times for the key generation cases thus comparing the capabilities of a modern mobile device and the average server. As we can see, the server is operating up to 30 times faster than the mobile device for the case of 1024 bits key size. By increasing this value to 4096 bits, the advantage grows to around 100 times. We therefore conclude that the key generation time of 100 seconds is unacceptable from the user's viewpoint. However, taking into consideration the key-length recommendations of today, 3 seconds may represent a feasible initial setup time.

Analyzing our PoC implementation, we model a scenario with four devices that have an opportunity to automatically accept or deny the addition/exclusion requests of the group members during the voting procedure (i.e., the case discussed in [209]). This application was modeled mainly to evaluate the network performance without any human-dependent delays and the corresponding results are given in Fig. 3.34. We decided to investigate here a more secure operation regime by utilizing 2048 bits keys. The provided plots include the time needed to establish a connection, conduct transmission, and perform data processing. These phases are executed independently of the user behavior and may thus become a useful reference point for future system implementations or improvements.

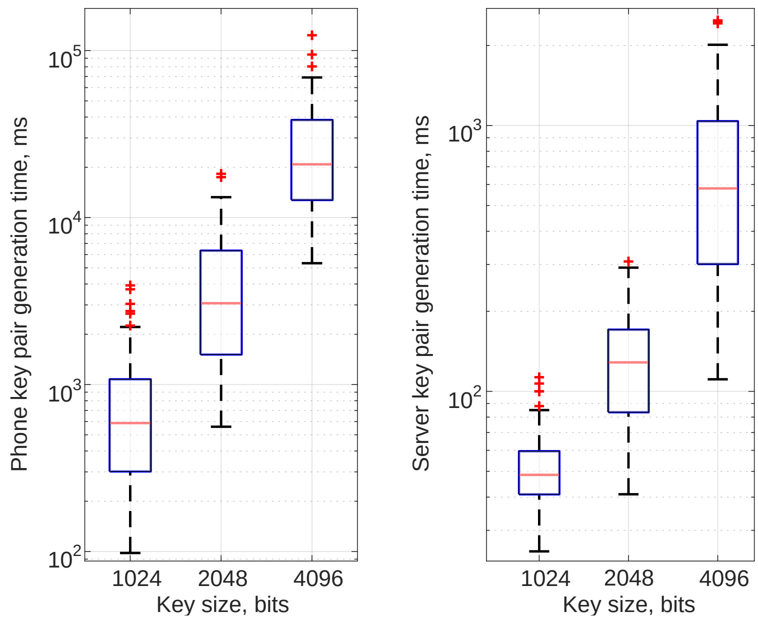


Fig. 3.33: Key pair generation time: server and user equipment [198], [200].

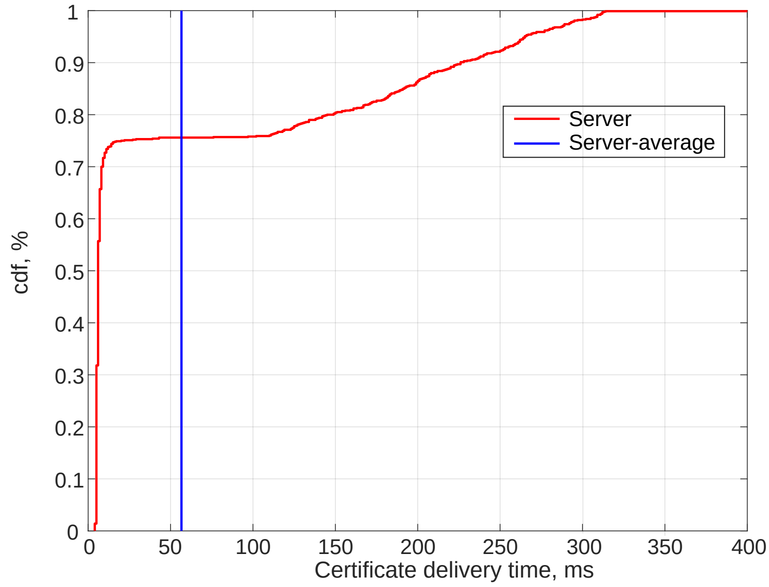


Fig. 3.34: Certificate delivery time (infrastructure mode) [198], [200].

As another important step of our analysis, we consider the operation of a purely ad-hoc mode i.e., when the connection to the cellular infrastructure is not reliable. The respective results are presented in Fig. 3.35. In this case, the procedure of the share generation for a new user takes approximately the same time as compared to the server-driven operation. The observed fluctuations are because of the unpredictable nature of the underlying random access mechanism of IEEE 802.11. It is worth noting that the time consumed by the system while excluding the user from an existing group may constitute up to 5 seconds even for smaller numbers of devices, which can directly affect the communications consistency.

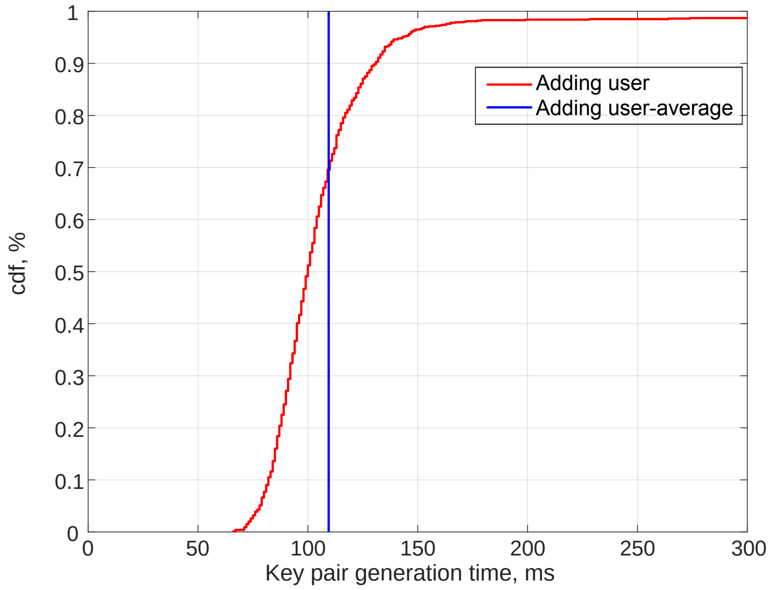


Fig. 3.35: Operation time in the ad-hoc mode – add user procedure [198], [200].

Interestingly, the "remove user procedure" takes more time than the "add user procedure", as evidenced by Fig. 3.36. The main reason why excluding a user consumes more time is because the corresponding protocol operates in the ad-hoc mode. In particular, to add a new device without the infrastructure connection, the trusted clients should cooperate and generate only one new share for this user to join. However, when excluding a device, the clients in the coalition should regenerate all of their own shares, which results in higher signaling and computation overheads.

Finally, our modified model was tested by evaluating the time required for the reconstruction of the secret on a contemporary smart phone. We thus considered the aforementioned Samsung Galaxy S4 device and the respective results are visualized in Fig. 3.37 – on the vertical axis, the time needed to reconstruct the secret is displayed by varying both the threshold value (the number of users in the coalition that have to be grouped) and the maximum number of users in the same group. Generally, the computation complexity of executing the information security primitives grows exponentially due to the properties of the Lagrange polynomial function. Moreover, adding another user to participate in this procedure brings at least 2 handshakes from the communication point of view. As the plot demonstrates, the proposed protocol requires less than 100 ms for the new share (point) generation for both joining and excluding procedures.

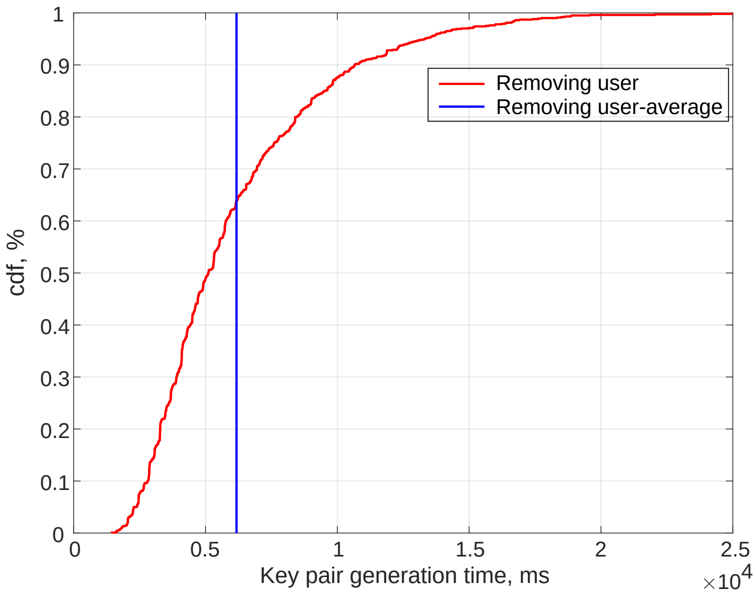


Fig. 3.36: Operation time in the ad-hoc mode – remove user procedure [198], [200].

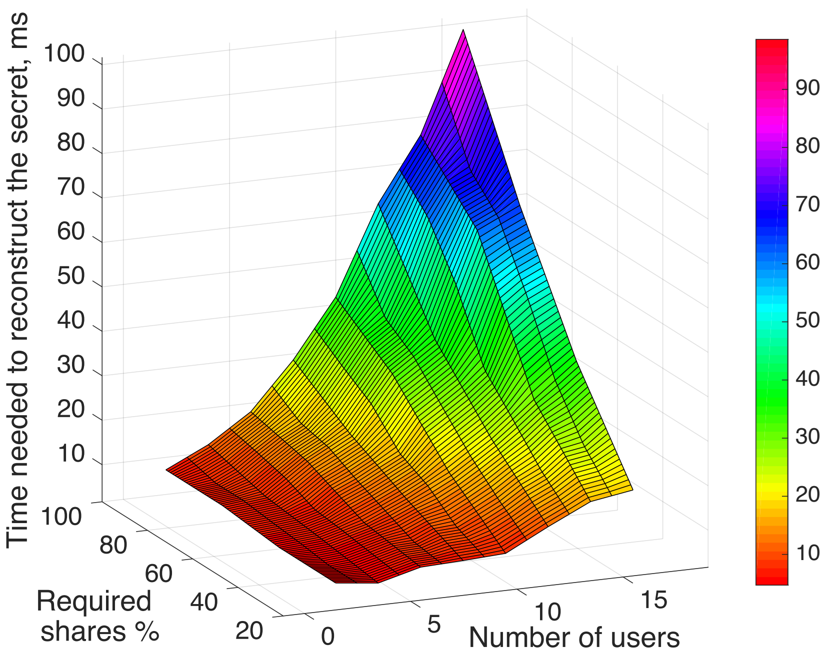


Fig. 3.37: Comparing the time to reconstruct a secret [200].

In conclusion, the developed protocol and the accompanying prototype implementation are suitable for utilization from both the user and the technology perspectives, where the main conclusions are summarized in Table 3.6.

Tab. 3.6: Summary of the PoC usability evaluation

Feature	Conclusion
Key size	Increasing the key size from recommended 1024 to 4096 bits brings a slight issue with the computation complexity on the mobile device side while utilizing 2048 bits is still acceptable (Fig. 3.33).
Initialization phase	In case when devices automatically confirm new joining users, the average certificate generation and delivery time takes less than 60 ms in the infrastructure mode (Fig. 3.34).
Unreliable cellular connectivity	While operating in the pure ad-hoc mode, adding a new user takes less than 120 ms on average, whereas excluding a user may consume up to 5 s in the worst case (Fig. 3.35).
Secret reconstruction	Time needed to reconstruct the secret grows exponentially, as the proportion of users that participate in the voting increases. Similar behavior is observed when increasing the overall number of users in the group (Fig. 3.36).

4 DYNAMIC ALLOCATION OF SPECTRUM RESOURCES

Next-generation (5G) communication networks will provide high bandwidth to mobile users via heterogeneous wireless architectures and dynamic spectrum access techniques. The inefficient usage of the existing spectrum can be improved through opportunistic access to the licensed bands without interfering with the existing users. Upcoming 5G networks, however, impose several research challenges due to the broad range of available spectrum as well as diverse QoS and QoE requirements of 5G applications. These heterogeneities must be captured and handled dynamically as mobile terminals roam between wireless architectures and along the available spectrum pool.

At the length of this section, we detail two application approaches, which were designed, implemented and verified using the experimental LTE deployment at Brno University of Technology (BUT), Czech Republic.

First part is dedicated to a practical evaluation of RAN modeling in indoor LTE deployment, where we benefit from the full access to the real LTE-A (Release 10) deployment and complete building documentation. The measured values of Signal to Interference plus Noise Ratio (SINR) and throughput are compared with the results from the radio signal propagation model, implemented in Python. The obtained values are in consequence used for the transmission power configuration to realize the Coverage and Capacity Optimization (CCO) in cellular networks.

In the second part of this section, we outline the functionality that is required by the LSA system to achieve the much needed flexible operation as well as report on the results of our respective live trial that employs a full-fledged commercial-grade cellular network deployment. Our practical results become instrumental to facilitate more dynamic bandwidth sharing and thus promise to advance on the degrees of spectrum utilization in future 5G systems without compromising the service quality of their users.

4.1 Transmission Power Optimization in 3GPP LTE-A Deployment

The growing demand for affordable mobile broadband connectivity is driving the development of Heterogeneous Networks (HetNets). A range of different cellular Radio Access Technologies (RATs) and WiFi will co-exist [210], and macro cells will be complemented by a myriad of smaller cells i.e., micro and pico cells. Services and next-generation application use-cases are another key drivers for indoor solutions as operators aim to provide users with the same or better QoS and QoE that they can receive outdoors [177].

In the past, the existing macro network was typically designed for mobility and outdoor coverage for voice services. Today, increased indoor coverage and broadband capacity is becoming more important as more data traffic H2H or M2M is consumed indoors. The main limitations of the existing macro network can be summarized as: (i) limited indoor coverage – due to building penetration loss (especially from modern buildings), (ii) inefficient use of spectrum resources particularly in urban and dense urban deployments, (iii) capacity limited, and (iv) relatively high cost for new deployments and upgrades [211], [212]. Many of these limitations can be overcome with various deployment options based on indoor coverage and capacity. Today's telecommunication operators have many deployment options to enhance coverage and capacity for indoor end-users. Macro cell enhancements, outdoor small cells and dedicated indoor deployment are options that can be used to further enhance the indoor user experience.

The in-band indoor deployment is the default option due to operators having limited spectrum resources. The deployment of indoor small cells answers the same challenges as outdoor small cell deployments, aside from the interference management benefits for natural shielding provided by the structure of the buildings. However, interference mitigation and the associated TX power management is still required between the indoor cells and both the outdoor cells and other indoor cells. Another aspect that must be taken into an account is high variability of the signal level in space and time (caused by walls and obstacles attenuating / reflecting the propagated radio signal).

In this section, the key output is to practically evaluate the interference mitigation technique based on the TX power management in indoor LTE deployment. We expand our previous research projects [213], [214] on prediction of network throughput and on the transmission power optimization. The TX power optimization scheme to maximize the throughput offered to the clients is proposed and tested on the 3-cell indoor TX network. Our employed LTE testbed, see Fig. 4.1, is composed of (i) the Radio Access Network (RAN) part, including one outdoor and four indoor small cells operating in the bands 700, 1800, and 2600 MHz, (ii) EPC part, and (iii) IMS part supporting VoLTE technology as well as Rich Communications Services (RCS).

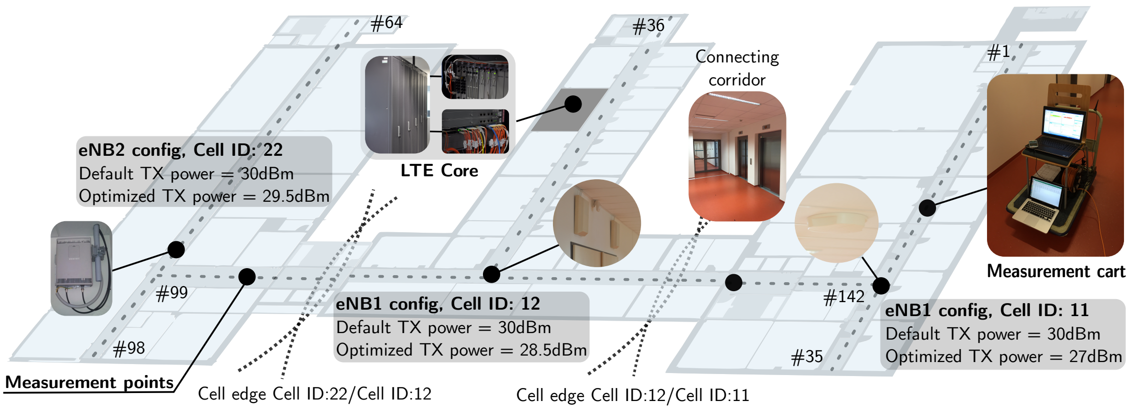


Fig. 4.1: Trialling LTE-A test bed for TX power optimization [213], [215].

As we had an opportunity to access and configure all parts of said LTE network and possibility to use professional radio network analyzer, we have compared the TX power configuration for considered LTE indoor deployment (obtained from developed PyLTE software [214]) with real data set measured by analyzer R&S TSMW Universal Radio Network Analyzer[11].

4.1.1 3GPP LTE-A Deployment and Proposed Methodology

The utilized experimental LTE-A (Release 10) network, see Fig. 4.1, stands for the complete commercial-grade implementation of all the crucial subsystems comprising contemporary 4th generation mobile networks. RAN comprises of two eNBs and one Home eNB. Indoors eNBs are divided into two elements: (i) Baseband unit (BBU), and (ii) Remote radio unit (RRU). ENodeB 1 composes two cells (denoted as Cell 11 and Cell 12) working in the band 17 (originally the AT&T band in US, 700 MHz). ENodeB 2 manages three cells (sectors) working at separated frequencies 700 MHz, 2600 MHz (these two are indoor pico-cells), and outdoor 1800 MHz.

While working on this research, we have used two cells from eNB 1 and first cell (named as Cell 22) in eNodeB 2 – all cells were working in band 17 (frequency 700 MHz). The rest of cells managed by eNB 2 was deactivated. The overall performed scenario is depicted in Fig. 4.1. As the eNB unit(s), the Huawei DBS3900 (fourth generation indoor macro base station) is utilized. It comprises of (i) BBU3900 (management logic for eNB e.g., mobility management of modulation techniques in base band), and (ii) RRU (modulation of used frequency).

TX Power Configuration and Limitations

Following the above text, we have focused in our study on configuration of TX power for individual eNBs. While working with the equipment provided by Huawei company, the TX power is possible to configure using the parameter "ReferenceSignalPwr" which is part of the physical downlink shared channel (PDSCH) object model and indicates the cell reference signal power of each physical antenna.

Therefore, it is necessary to set *ReferenceSignalPwr* appropriately to ensure a reasonable trade-off between coverage and capacity, effective channel estimation, and appropriate interference control. Impact of the *ReferenceSignalPwr* on the radio network performance is detailed below:

- Coverage: If the value of ReferenceSignalPwr is too large, cross-coverage occurs. This causes interference to other cells. If the value of ReferenceSignalPwr is too small, coverage holes appear.
- Interference: The setting of ReferenceSignalPwr varies with the interference from neighboring cells. A large interference margin is required, where the interference is strong.
- Channel estimation: A larger value of ReferenceSignalPwr leads to higher channel estimation accuracy, a lower demodulation threshold, and higher receiver sensitivity, but it causes stronger interference to neighboring cells.

[11] See R&S TSMW Universal Radio Network Analyzer: `https://www.rohde-schwarz.com/us/product/tsmw-productstartpage_63493-10072.html`

- Capacity: A larger value of ReferenceSignalPwr brings better coverage, but also limits the power used for the transmission of data and hence decreases the system capacity.

While configuring the network parameters, we have been able to change the TX power in range from 26 dBm to 30 dBm. The upper limit for LTE deployment (maximal TXpower) is defined by the Czech telecommunication office and equals to 1 watt. In contrast, the lower limit should not be in theory limited.

Nevertheless, using the Huawei equipment in our test bed, we have observed that the minimal value of TX power equals to 26 dBm which corresponds to 0.39 watt[12]. Based on this restriction, we have decided to declare the range for TX power from 26 dBm to 30 dBm with step 0.5 dBm. This configuration was used as the input data set for our PyLTEs software [214], which is described in following text.

Network Optimization Procedure in PyLTEs

Based on the previously verified model [213], we ran an optimization procedure to achieve highest possible network parameters in given TX power limitations. As a reference to the measured network performance, we used the same points in the building, see Fig. 4.1. The procedure looks as follows:

Data: The best $\leftarrow -1$
Result: Optimized TX power configuration for *BS1*, *BS2*, *BS3*
begin
  for $Tx_{BS1} \leftarrow$ *Lower Limit to Upper Limit* **do**
    for $Tx_{BS2} \leftarrow$ *Lower Limit to Upper Limit* **do**
      for $Tx_{BS3} \leftarrow$ *Lower Limit to Upper Limit* **do**
        $current \leftarrow ReturnSumOfAllClientsMCS$;
        if $current > TheBest$ **then**
          $TheBest \leftarrow current$
          $Best_{BS1} \leftarrow Tx_{BS1}$
          $Best_{BS2} \leftarrow Tx_{BS2}$
          $Best_{BS3} \leftarrow Tx_{BS3}$
        end
      end
    end
  end
end

Algorithm 3: Optimization Procedure in PyLTEs

The step for iterators over TX power was set to 0.5 dB. After the procedure, variables BestBS1, BestBS2, BestBS3 are configuration outputs of TX power for the network.

[12]The maximal TX power possible to set using the Huawei equipment (without the restriction from the Czech telecommunication office) is equal to 42 dBm (15.84 watts).

Function *sumOfAllClientsMCS()* returns sum of maximal possible throughput calculated from MCS table for each sampling point. SINR level is calculates as shown in 4.1:

$$SINR = \frac{P_{tx} - PL}{\sum_{BS_{vis}} (P_{tx} - PL) + N}. \tag{4.1}$$

Proposed method evaluates all possible solutions and picks the best one. It is possible, because the number of possible solutions is relatively small. As it was shown in [216], the TX power optimization is a NP-hard problem. For networks with higher number of eNBs (e.g., hundreds of base stations), some other method to find good enough solution can be used (e.g., metaheuristic methods).

4.1.2 Evaluation of Optimized LTE-A Network Configuration

In order to be able to test our newly configured LTE-A network, we have used the professional R&S TSMW universal radio network analyzer together with the shipped ROMES software. While working on the practical evaluation of configured settings, we have prepared the mobile measurement cart, see Fig. 4.1, equipped by (i) analyzer, (ii) laptops for management of the analyzer properties and network configuration, and (iii) generic smartphone Samsung Galaxy S4 supporting band 17 (phone was shipped with the installed stock operating system Android 4.4.2 from AT&T telecommunication operator).

The methodology of performed measurements can be divided into following steps:

1. Measurement points allocation: As depicted in Fig. 4.1, the floor is divided into three corridors and one connecting corridor. The whole floor was marked by 142 measurement points with the distance 1.5 m between neighboring points. The time slot for measurement at each point was set to 180 seconds (during this time period, approximately ten thousand samples were captured by analyzer and processed later offline). All parameters were set exactly the same as in our pre-evaluation measurement [213] which enabled us direct comparison.
2. Performed tests: At each of the measurement points, the values summarized in Table 4.1 were measured by analyzer and smartphone.
3. Selecting the eNB: The UE was measuring the values of the RSSI and based on the obtained value, the connection to the best pico-cell in actual range was realized. The selection of the best pico-cell candidate follows the signal quality level, which is influenced primarily by the thermal and acoustic insulation used indoor and also by wall materials (reinforced concrete, clay block masonry, autoclaved aerated concrete, and gypsum board). We have compared the selected cell at each measurement point (analyzer vs. smartphone) and as we had an opportunity to access data from previous measurements [213] it was possible to correlate obtained information about the selected pico-cell for the configured TX power scenarios.

Tab. 4.1: Measured parameters: (i) universal radio network analyzer and (ii) smartphone.

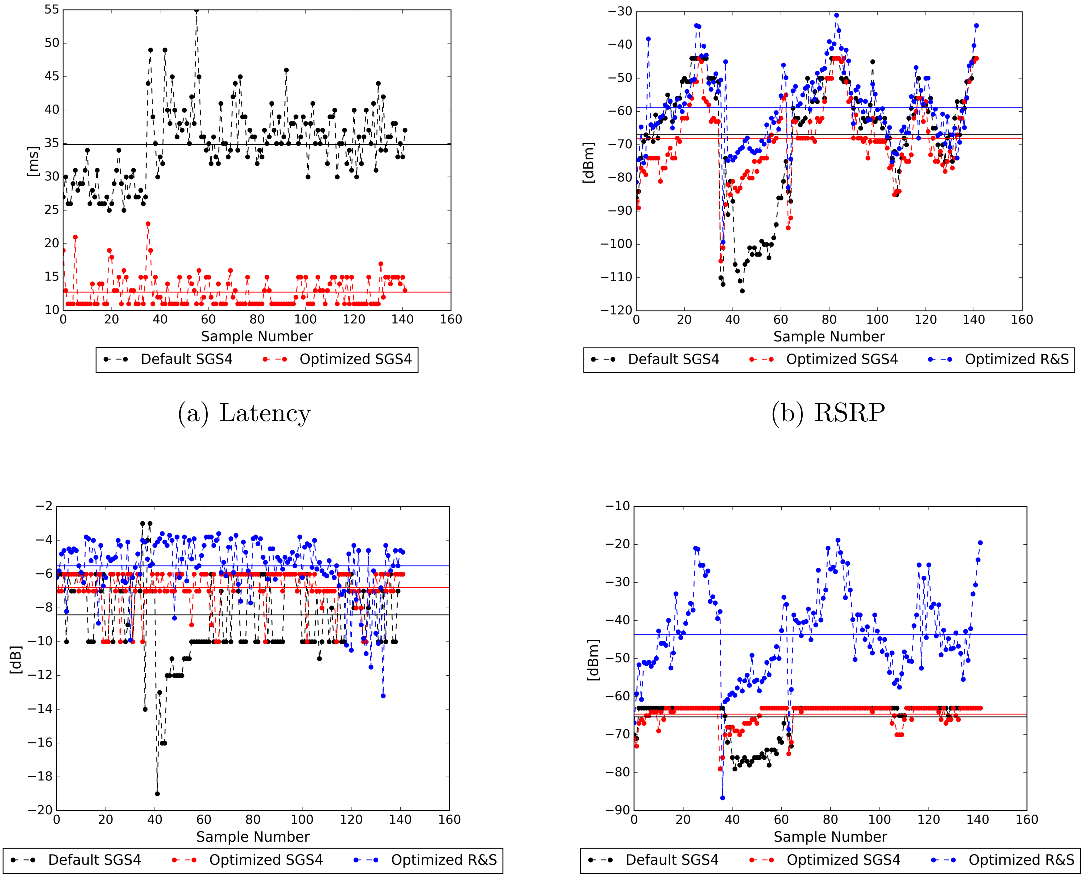
	Parameter	**Description**
Analyzer and Smartphone	Power [dBm]	Received Signal Power in dBm on S-Sync.
	RSRP [dBm]	Reference Signal Received Power in dBm measured on the 6 innermost resource blocks.
	RSRQ [dB]	RSRQ in dB. Based on RSRP and the total inband power in resource blocks used to transmit the PBCH within the 100ms IQ data block.
	SINR [dB]	Signal to Interference plus Noise Ration in dB.
	Cell Number [-]	ID of selected cell.
Analyzer	WB RSRQ [dB]	Max. RSRQ in dB based on wideband measurement.
	WB RSRP [dBm]	Max. Reference Signal Received Power in dBm in the configured wideband bandwidth.
	WB RSSI [dBm]	Max. Received Signal Power in dBm based on the wideband measurement.
	WB RS RSSI [dBm]	Max. Received Signal Power in dBm based on wideband measurement according to 3GPP definition.
	WB RS–SINR [dB]	Max. SINR in dB measured on Reference Signals in the configured wideband bandwidth.
	RS SINR [dB]	SINR in dB measured on Reference Signals in the 6 innermost Resource Blocks. The maximum of all measured antenna ports.

Obtained Results

To adequately evaluate the obtained data of utilized devices (analyzer and smartphone), we have selected following network parameters as the most important ones: (i) network latency between smartphone (UE; end-terminal) and remote server, (ii) Reference Signal Received Power (RSRP), (iii) Reference Signal Received Quality (RSRQ), and (iv) Signal to Interference plus Noise Ratio (SINR).

Fig. 4.2a provides the comparison of the network latency measured with the default TX power configuration (all cells configured with TX power 30 dBm) and data measured with new, optimized scenario, where the cells were configured as follows: (i) Cell11 = 27 dBm; (ii) Cell12 = 28.5 dBm; (iii) Cell22 = 29.5 dBm. As it can be seen, the data from optimized scenario supports the performed changes in the RAN part of LTE-A test bed since the latency is significantly lower for all measured points - lines in the graph represent the mean values of obtained data.

This behavior is verified when looking in the Fig. 4.2b, data from smartphone (Optimized SGS4) and analyzer are close to each other and the significant drop measured last year with default configuration of TX power (Defalut SGS4) is no longer measured. Based on the data from the Fig. 4.2b, Fig. 4.3a and Fig. 4.3b, we can also observe that RSRP from the eNBs increased (on the average) by 1.5 dB (working with the MCS table, the width of one modulation level is $\sim$1.81 dB). At the end, we can conclude that the average RSRP increase gave us (in utilized scenario) an increase of throughput on average.



(a) Latency (b) RSRP

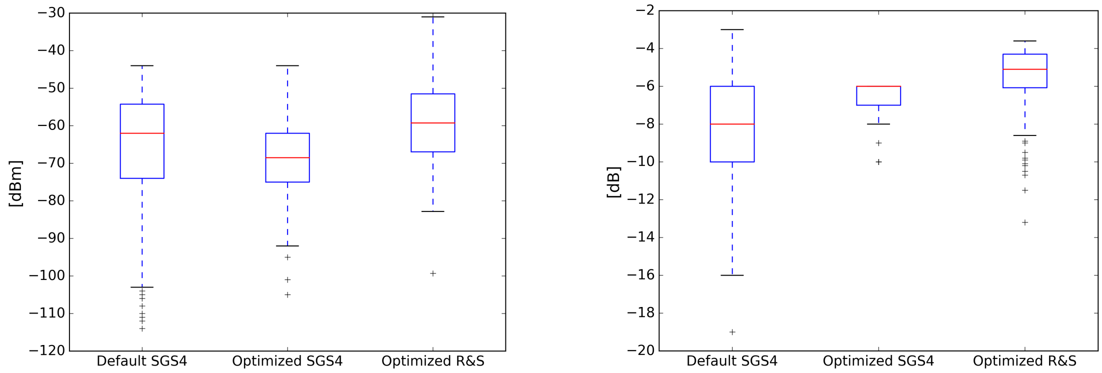
(c) RSRQ (d) RSSI

Fig. 4.2: Comparison of the (a) Latency, (b) RSRP, (c) RSRQ, and (d) RSSI calculated by analytical model (data from our previous measurement is named as *Default SGS4*) and measurement in our real LTE-A indoor test bed (data from analyzer (for optimized TX power configuration) is marked as *Optimized R&S*) [213], [215].

In Fig. 4.2c, we can observe the additional information to the RSRP. RSRQ is defined as the ratio *N×RSRP/(E-UTRA carrier RSSI)*, see Eq. 4.2, where *N* is the number of Resource Blocks (over which the RSSI is measured; typically equal to system bandwidth) of the E-UTRA carrier.

$$RSRQ = N_{prb} \times \frac{RSRP}{(E - UTRA_{carrier} RSSI)}. \tag{4.2}$$

The reporting RSRQ is defined in range from -3 to -19.5 dB [217]. At the end, we can say that the RSRQ depends on the serving cell TX power and the number of TX antennas. Therefore, we can conclude that the optimized TX power scenario (even the modification for e.g., Cell22 was 0.5 dB (from 30 dB to 29.5 dB)) was reached – this fact is also confirmed in Fig. 4.2d, where the SINR obtained from default and optimized configuration (smartphone) and analyzer is depicted. The heat-map showing the calculated values of SINR for optimized TX power scenario in the utilized environment is shown in Fig. 4.4.



(a) RSRP (b) RSRQ

Fig. 4.3: Detailed depicting of obtained data for RSRP and RSRQ through the quartiles together with outliers (default and optimized scenario are included) [213], [215].

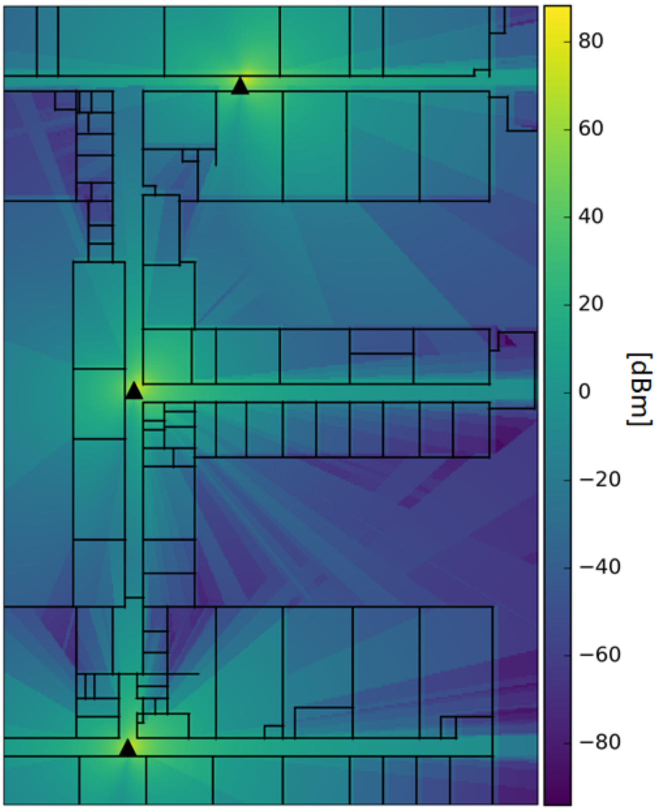


Fig. 4.4: Signal heat map calculated by the PyLTEs tool for the LTE-A indoor deployment [213], [215].

Lessons Learned

In the process of configuration the said TX power optimization mechanism, we have addressed a number of challenges regarding the used LTE-A deployment. As mentioned in the previous sections, our LTE-A test bed is provided by Huawei company. Since the way of configuration varies on the manufacturer (Huawei, Ericsson, etc.) we have tried to identify the common parts for all LTE / LTE-A deployments (and implementations) aiming to the universal mechanism for TX power configuration.

To this end, we have implemented the said mechanism with respect to the physical downlink shared channel (PDSCH) object model – indicates the cell reference signal power of each physical antenna. While configuring the TX power for our PyLTEs simulation tool, we have observed the limitation of the range of possible TX power in real LTE-A indoor deployment: from 26 dBm to 30 dBm. Based on this observation, we have modified the PyLTEs simulator to produce precise data set for our simulation.

Our main and the most essential learning while configuring the TX power is such, that the optimized scenario improved the latency for end-terminals (see the Fig. 4.2a) from 35 ms (mean value) to 12 ms. Even that the range for configuration of TX power was limited by the network settings (from 0.39 W to 1 W) we have shown that the correlation between the obtained data from analyzer and data from PyLTEs simulator improved (in comparison with our previous research work, see Fig. 4.2b, Fig. 4.2c, Fig. 4.2d). In summary, the discussed implementation may become an important consideration for TX power configuration as the proper configuration of TX power in today's mobile indoor deployments, even with respect to the Self-Organizing Network (SON)[13], may have difficulty to satisfy the user requirements (QoS, QoE) [213], [215].

[13]SON has been codified within 3GPP Release 8 and subsequent specifications in a series of 3GPP standards.

4.2 Highly Dynamic 5G-Ready Spectrum Management with Licensed Shared Access

The 5G wireless systems aim to decisively advance on the levels of spectral and energy efficiency, user-experienced throughput, as well as communication latency and reliability. They are expected to rely on leveraging extremely high frequency (i.e., mmWave) spectrum bands, employing massive Multiple-Input Multiple-Output (MIMO) techniques, as well as deploying increased numbers of small cells with various sizes and across different frequencies. However, the use of mmWave radios is costly and the key enabling technology is still under standardization, whereas massive MIMO requires complex and expensive coordination that is difficult to achieve in practice. Therefore, the main feasible method to offer larger capacity on existing cellular deployments is via extreme network densification [218].

The mobile network operators (5G) are however struggling to deploy a higher density of small cells due to the need of extra investment that is not compensated by the actual revenues [219]. On the other hand, multiple field measurement campaigns strongly show that the conventional spectrum below 6 GHz may be substantially underutilized across space, time, and frequency [220]. This is a consequence of the legacy "command-and-control" spectrum management approach that used to create static and overprotective allocations[14]. Hence, as a viable alternative to deploying additional small cells, the MNOs may quickly augment capacity on their deployments – more *dynamic* and market-friendly spectrum management mechanisms should be made available in the emerging 5G systems [221].

With more dynamic spectrum management, the expensive frequency bands could be shared between different stakeholders flexibly, as opposed to exclusive use of licensed spectrum. This may go far beyond opening up unlicensed frequencies for collective uncontrolled use and promises to unlock the much needed additional bandwidth, that is currently employed sparsely by its existing incumbents. It can also improve the utilization of presently allocated spectrum across its various dimensions (space, time, frequency), which is essential to support the throughput-hungry 5G applications. To this effect, powerful spectrum sharing technologies emerged recently, such as LTE in unlicensed spectrum (LTE-U), License Assisted Access (LAA), MulteFire, Citizens Broadband Radio Service (CBRS), and Licensed Shared Access (LSA) [222].

The LSA framework is an evolution of the industry-driven Authorized Shared Access (ASA) technology for controlled spectrum sharing between the incumbent holding the rights to use the frequency bands and the licensee (e.g., the MNO), who is utilizing such spectrum temporarily[15]. This concept has been taken forward by the European Commission (EC) to develop a new "individual licensing regime" for authorized spectrum sharing [223]. According to the EC's Radio Spectrum Policy Group (RSPG), the LSA

[14] Spectrum Efficiency Working Group, Report of the spectrum efficiency working group, Federal Communications Commission, 2002.

[15] Frequency Management Working Group (WGFM), "Report on ASA Concept, FM(12)084 Annex 47", 2012.

framework enables a limited number of licensees to operate in a frequency band already assigned to one or more incumbents in accordance with well-defined sharing rules. As a result, all of the authorized users, including the incumbents, can maintain their desired Quality of Service (QoS) requirements (RSPG 13-538) [218].

Ever since its introduction several years ago, the LSA concept has spawned an avalanche of engineering, business, and regulatory work that focused on adapting it promptly to practical applications [224]. This development has been facilitated by the Conference Europeenne des Postes et des Telecommunications (CEPT) as it had established two project teams, PT52 and PT53 (ETSI TS 103 113), to ensure that there are no barriers to the adoption of LSA in 2.3 – 2.4 GHz bands from a regulatory perspective[16] [225]. In parallel, ETSI has been targeting to outline the LSA system architecture in their respective technical specifications (ETSI TS 103 154) and (ETSI TS 103 235). In the US, a Notice of Proposed Rulemaking (NPRM) in 3.5 GHz band was introduced by the FCC[17] [226].

As a result of this concentrated effort, the LSA has soon been ready for practical demonstrations, which took place in Spain (2015), Italy (2016), France (2016), Finland (2016), Czech Republic (2016), and the Netherlands (2017). However, many of these past activities considered near-static LSA operation with longer-term allocations since they primarily addressed the technical feasibility of LSA implementation [227]. Building on our previous conceptual work in [228] and technology groundwork in [229], we here complement these earlier initiatives with a new perspective on highly dynamic spectrum management within the LSA framework. In this section, we specifically emphasize the QoS aspects and the corresponding service reliability performance as discussed work unveils the limits of dynamic LSA operation based on a practical trial in a live LTE-A system [218].

4.2.1 Dynamic Spectrum Management with LSA

With the emerging LSA framework, flexible and more dynamic spectrum sharing may be enabled, which becomes increasingly valuable for demanding 5G applications [230]. The advanced services that can benefit from cross-band spectrum aggregation are those that require massive bandwidths, but have difficulty to be supported by the existing MNO deployments (e.g., augmented and virtual reality) [231]. Another category that may take advantage of highly dynamic LSA operation is industrial Internet of Things (IoT) applications across different verticals, especially those requiring reliable operation and dedicated QoS guarantees (e.g., automotive). Finally, LSA can improve a wide range of local broadband services, such as those where the MNOs do not have a possibility to deploy exclusive licensed spectrum (e.g., enterprise) [232], [233].

Therefore, we expect that as LSA technologies mature, an increasing variety of 5G applications and services will be capable of taking advantage of more efficient geographic-temporal spectrum management. In [228], the LSA functionality required to enable truly dynamic spectrum sharing at the timescales of seconds is outlined. These capabilities

[16] EC Mandate on MFCN for 2.3 - 2.4 GHz, 2014.

[17] Enabling Innovative Small Cell Use In 3.5 GHz Band NPRM & Order, 2012.

are crucial for incumbent systems with high-speed mobility (e.g., express trains and airplanes) and may offer much improved performance compared to rigid and near-static LSA implementations. Given that LSA is an example of vertical sharing (see Fig. 4.5a), multiple spectrum users across the same geographical area can operate at different priority tiers. For instance, the LSA licensee (e.g., a commercial LTE network) may avoid causing interference to the LSA incumbent (e.g., an air traffic control system).

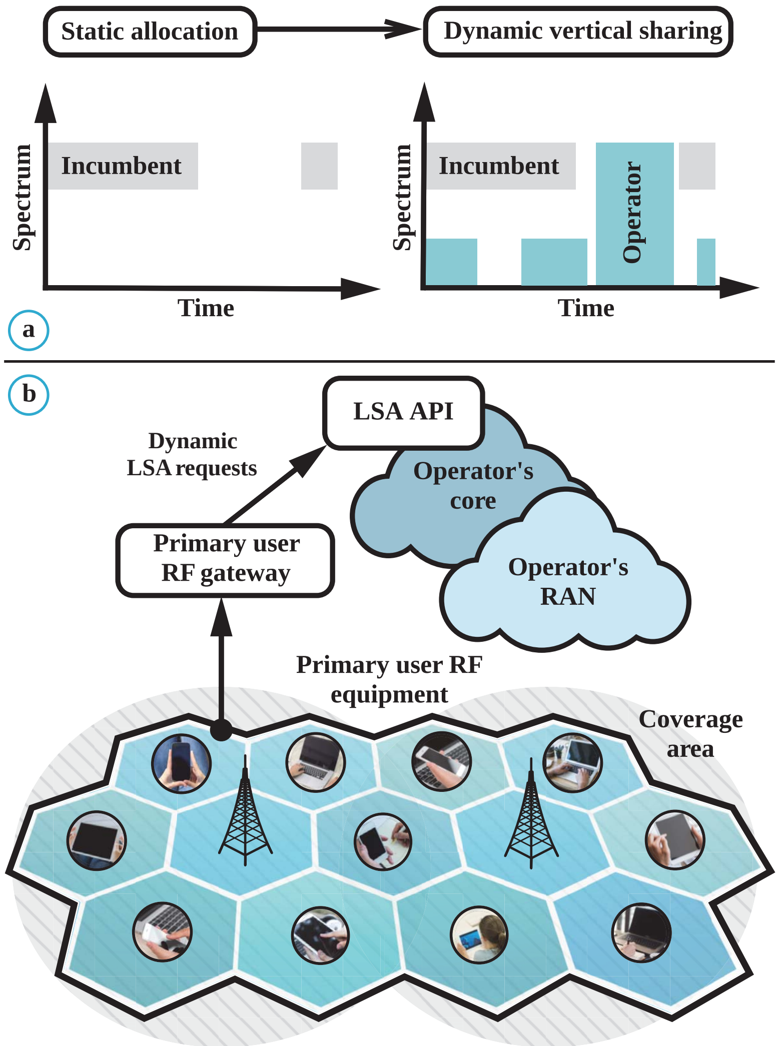


Fig. 4.5: (a) Improved spectrum utilization with dynamic sharing; (b) High-level architecture of dynamic LSA operation [218].

Our envisaged dynamic LSA system is intended to operate according to the high-level architecture captured in Fig. 4.5b. The primary user of the spectrum (i.e., the incumbent) identifies its target constraints (across space, time, and frequency), where the wireless interference constraints have to be met by the secondary user (i.e., the LSA licensee, such as the MNO). Further, a corresponding LSA request is issued and transferred to the operator's dedicated API, where it is then converted into specific RAN instructions (e.g., interference estimation, transmit power reduction, frequency band change, LSA spectrum usage policy, etc.). Once these commands are received by the operator's cloud, its RAN executes the required actions as instructed.

Considering the key mechanisms and constraints in place for dynamic LSA systems, the proposed functionality as discussed below enables the RAN to respond to the received LSA-specific requests issued by the incumbent in near real time. The primary benefit of our approach is in flexible bandwidth segmentation, which is much more fine-grained and adaptive than in previous LSA implementations. With such dynamic and on-demand network configuration, substantial radio resources can be made available to both the incumbent(s) and the LSA licensee(s), since the proposed logic tightly applies to the time domain. Accordingly, the timescale of radio resource utilization has higher granularity than in static LSA approaches. At the time instant, when the incumbent does not utilize its bandwidth resources, they are released automatically, without any additional administrative overheads or delays associated with the LSA database updates.

In addition, our approach efficiently leverages the spatial dimension of the shared spectrum resources. That is, the locations, where the bandwidth has to be released by the LSA licensee (the MNO) back to the incumbent, can be obtained with higher precision than what is possible with the conventional LSA setups, in which the geographical blocks are typically represented as a coarse grid on the map. In the following sections, we continue by providing a systematic perspective on our development efforts to implement a dynamic LSA system. We also highlight our crucial design choices with regards to the communication chain that facilitates near real time LSA operation within a practical LTE network deployment.

4.2.2 Principles of Dynamic LSA Implementation

Based on the above considerations, we expect that upcoming LSA implementations will require software and hardware modifications within the existing cellular network infrastructure as well as, potentially, on the side of the UE. Despite substantial ongoing efforts to evolve the LTE system as one of the 5G cornerstone technologies, a support for highly dynamic LSA operation in practical MNO deployments calls for a dedicated technology development effort. If not reflected comprehensively in further LTE releases, the LSA spectrum sharing mechanisms may be slow to enter the market, where they are much needed at this time. In this section, we address this important demand by exposing the key system functionality required to support highly dynamic LSA in a 3GPP LTE system.

Proposed components and functionality

We remind that wireless technology standardization conventionally begins by defining the functional elements and interfaces between them. Aiming to lay the groundwork for this, we first identify the main functions and interfaces necessary for implementing dynamic LSA mechanisms (see Fig. 4.6). Given that we have recently outlined the core principles behind the dynamic LSA framework as a proof-of-concept study in [229], we build the present system architecture proposal on our rich hands-on experience acquired then. To this end, we rely on a full-fledged cellular system deployment at Brno University of Technology (BUT), Czech Republic, which offers an excellent example of a contemporary 3GPP LTE-A target system.

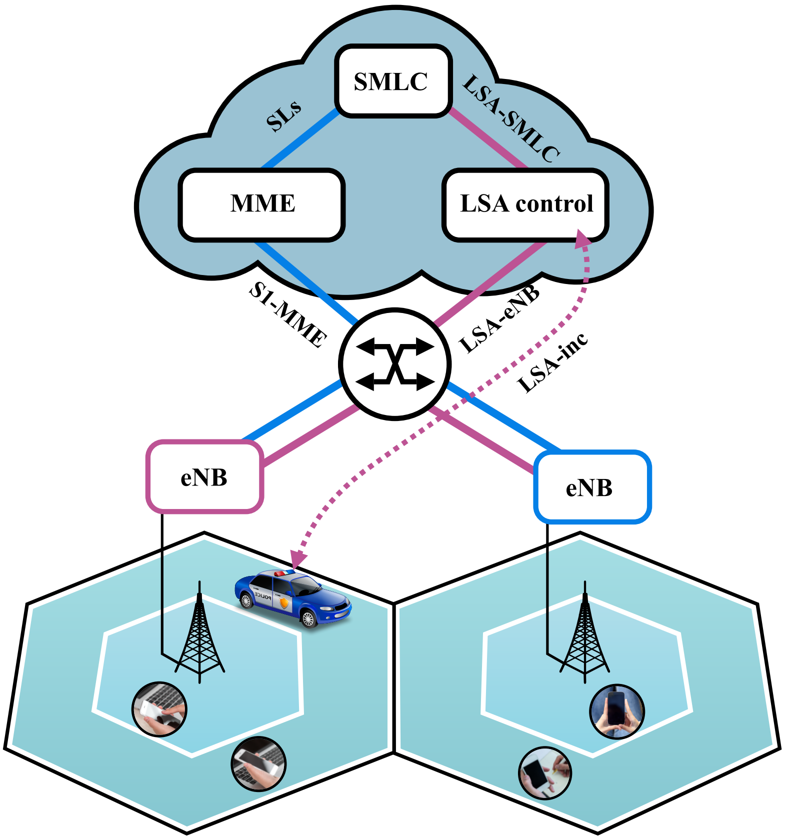


Fig. 4.6: Key elements of proposed dynamic LSA architecture [218].

Control is responsible for accepting the incumbent's requests and managing the power allocation across the network. In conventional LSA systems, this function could be performed by the LSA controller, while the LSA repository acts as a proxy. For the intended highly dynamic operation, we advocate for the need of a direct interface between the incumbent and the LSA controller to reduce control-plane latency (LSA-inc).

Positioning is used for locating the sources of interference in the network, which is key to efficient power allocation. In cases when the LSA band is utilized for downlink (DL) communication, the positions of all LTE eNBs are typically well-known, and may thus be programmed into the controller. However, in cases when the LSA is applied to uplink (UL) or TDD bands, it is important to have the position estimates of the UEs as well, since they become the main sources of interference. Currently, such information is not available to the LSA controller, and we propose to introduce the LSA-SMLC interface, which would allow the LSA controller to directly access the LTE positioning data (as calculated based on the cellular signals or reported by the UEs themselves).

Policy Assignment offers the capability to issue commands to the individual cells, which is at the very core of the LSA concept. In our dynamic LSA system, this implies setting transmit power constraints for the corresponding radio interfaces – in the limit up to full cell shutdown. However, a commonly overlooked issue is that shutting down a particular cell does not necessarily eliminates the interference coming from its service area. This is because some UEs may associate (or remain associated) with a neighboring cell and thus continue their transmissions on the LSA bands for the extended periods of time. The use of OA&M interface (as proposed by 3GPP and utilized in static LSA trials) may therefore become insufficient to implement the control decisions with the required levels of responsiveness. The LTE-eNB interface indicated in our diagram (see Fig. 4.6) aggregates (i) functions normally accessible via OA&M (set the transmit power, shut the cell down, etc.) as well as (ii) certain instructions given directly to the UE via the RRC interface (e.g., initiate handover to a specific cell, switch the band, etc.).

Envisioned LSA System Operation our proposed system design targets to ensure that the dynamic LSA framework can achieve the highest degree of control accuracy. To this end, we enable the UEs to know their precise location (which can even be acquired indoors if desired), and make them report it to the SMLC. This information can then be extracted from the SMLC via a proprietary system monitoring interface, which acts as LSA-SMLC. The control interface LSA-inc can be implemented as a JSON structure (via socket), over which the current coordinates and the threshold power settings could be reliably reported with the minimal delay by each of the incumbent's users, thus defining a constraint in the controller's power allocation algorithm. Unlike in the static LSA cases, dynamic reports are transient in nature and time out on their own. Hence, the network reverts to its default operation whenever no more reports are being sent. For our below test measurements, such reports were triggered manually.

Most importantly, to address the increased control granularity in the dynamic LSA system, the LSA-eNB interface needs to be implemented as a combination of the OA&M and the direct UE control. One of our core proposals, that are instrumental to the dynamic LSA operation, is to reduce the transmit power instead of a complete cell shutdown, which considerably improves system capacity. While it is relatively easy to lower the UL or DL power limit in a cell instead of shutting it down, actually ensuring it in the UEs that are thus forced outside of the cell's coverage area is much more difficult. In our setup, the DL power control has a few possible settings that match the cell coverage area in the DL with its intended service area in the UL.

In a commercial-grade test deployment, it may be cumbersome to send the RRC control signals from the core network that would enforce the UE handover out of the LSA band (as UEs prefer to handover inside their current band when a cell is shut down). To mimic this functionality, the UEs may employ a user-space program that would shut them down instead. Further, the UEs that fall out of the service area of a particular cell – but still able to receive its DL signaling – may, according to their protocol, attempt a RACH

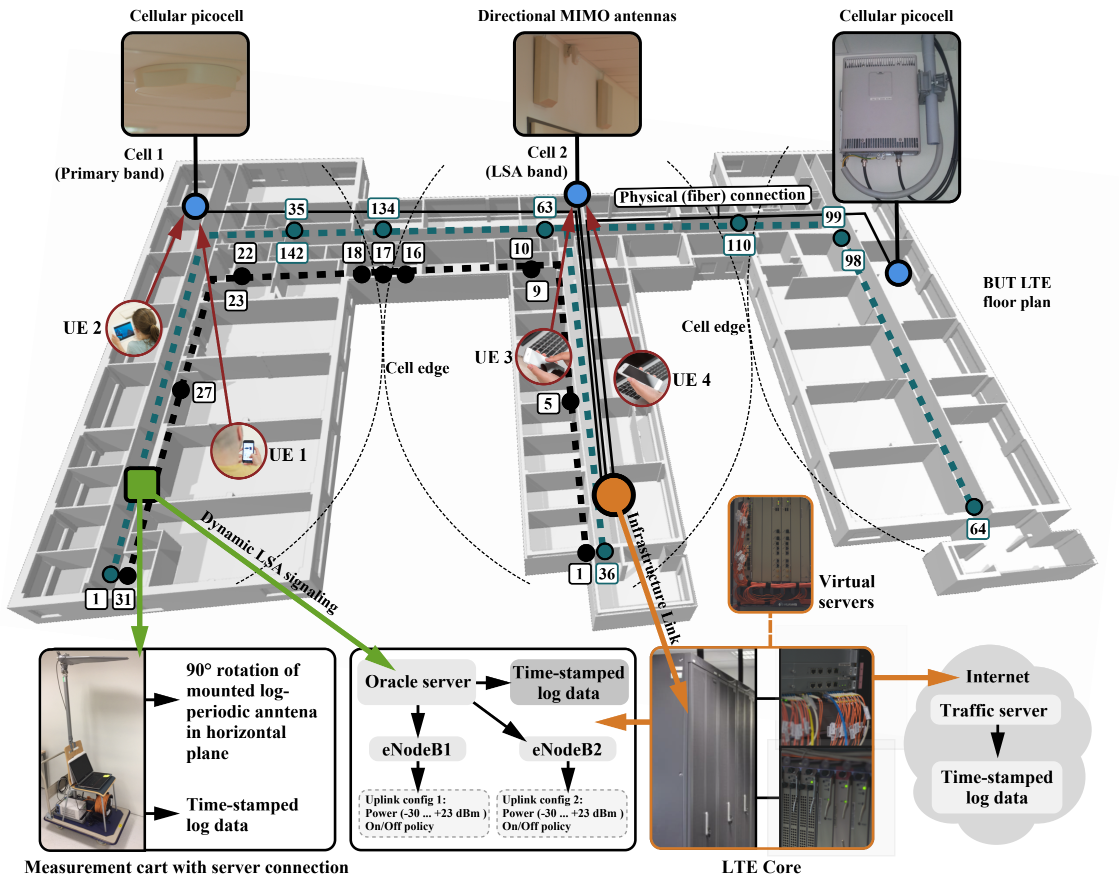


Fig. 4.7: Implemented dynamic LSA setup (architectural components) in our test 3GPP LTE infrastructure [218].

procedure. These RACH transmissions use power ramping if unsuccessful (and they will be unsuccessful as the cell is instructed not to accept the initiating UEs), and may thus violate the interference constraints. While RACH packets are only short bursts, they may still cause issues in certain cases.

4.2.3 Important practical considerations

Out of the three interfaces identified for the needs of dynamic LSA operation (see the previous section), only two are deployment-ready today. Indeed, reporting the desired interference constraints may be readily achieved with existing IP-based protocols, while connecting the SMLC with the LSA controller is fairly straightforward. On the contrary, ensuring that all of the UEs follow the dynamic power allocation policy in a predictable manner is complicated due to certain limitations in current cellular signaling:

- The UEs cannot be forced to handover away from their current serving eNB without a deep integration into the proprietary code inside the MME. While the required functionality may be made available by some of the core network vendors, it is presently not a part of any standard specification. Similarly, UE's handovers between the individual cells under the same eNB may not be even reported to the MME, which translates into the need for more proprietary interfaces as of today.

- The service area of a cell with the reduced UL power level may not be easily predicted by the UEs, thus often resulting in futile RACH attempts by the devices that are relatively far away from the cell center (and given its UL power limits). Adding the relevant information elements into the beacon signal could certainly allow to improve on this, but it is neither supported by the current beacon formats nor available in the practical eNBs utilized for testing.

Our LSA controller implementation utilizes all of the needed interfaces together with the relevant power allocation policies that are discussed in the following section. Its current version employs a heuristic iterative search procedure to locate the optimal power assignment across all cells in order to match certain performance targets (e.g., maximize the throughput or minimize the number of users that lose service). For the most unsatisfied constraint, a simple algorithm is applied in a loop: a vector of the expected reduction in interference for a 1-dB reduction of power in cell i is computed, and the most impactful cell is chosen. The power in this cell is then reduced by 1 dB and the vector is updated (with its sorted order restored). Once the constraint at hand is no longer the most unsatisfied, another constraint is chosen to proceed further. When all of constraints are satisfied, the search is complete.

The asymptotic complexity of our proposed algorithm is $O(C \cdot R)$, where C is the number of cells and R is the number of constraints (e.g., incumbent's devices) in the system. The resultant power allocations may be then stored and used to initialize the subsequent runs, thus further reducing the time needed for reaction. This means that proposed solution can be scaled up to hundreds of cells if desired, without much sacrifice in the response times. To summarize, our proposed system implements all of the dynamic LSA functionality. While some of its components may not be production-ready as of yet (i.e., the LSA-eNB interface) due to the limitations in the underlying LTE subsystems, it clearly confirms that the considered system is not only feasible, but may also be deployed in larger cellular networks with reasonable effort [218].

4.2.4 Measurement Methodology and Obtained Results

To systematically demonstrate the outlined principles of highly dynamic LSA operation in practice, we conducted a full-scale real-world implementation of our capable LSA-based spectrum sharing system in a commercial-grade 3GPP LTE channel and evaluated its availability over the LSA frequency bands. The UL system has been preferred due to its significantly higher implementation complexity as compared to the DL LTE channel, which also led to more interesting observations. The primary system-level parameters are summarized in Table 4.2, while the composition of our trial implementation is detailed in Fig. 4.7.

The UEs under test were continuously communicating with the data server located in the Internet, which recorded their effective UL and DL bit-rate values over time. Prior to

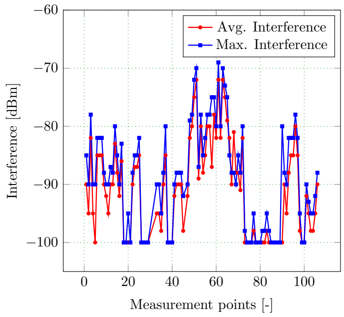
Tab. 4.2: Main system-level parameters.

Description	**Value**
3GPP LTE system baseline	Release 10
Division multiplexing	FDD
Number of cells (eNBs)	3
Frequency band	17 (700 MHz)
Bandwidth	5 MHz
Number of resource blocks (RBs)	25
Max. eNB power level	0 dB
Min. eNB power level	-30 dB
Interference threshold	-85 dBm
Path loss coefficients	5 dBm (concrete) 2 dBm (gypsum)
Pathloss model	Enhanced FSPL
Number of terminals (UEs)	4
Transmission data rate	512 kbps
Frequency analyzer	R&S TSMW
Antenna	HL040 log-periodic broadband

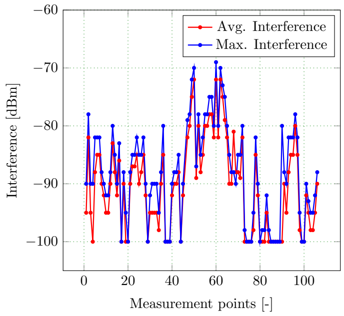
taking measurements, the UEs were configured to target a constant bit-rate (CBR) transmission at 512 kbps, if sufficient radio resources were available; otherwise, they utilized all of the remaining UL resources subject to the current transmit power restrictions. The trial focused on analyzing the LSA band and demonstrating its highly dynamic operation. Hence, the UEs were forced to close the connection whenever they were supposed to switch over to the non-LSA frequencies.

Power allocation policies

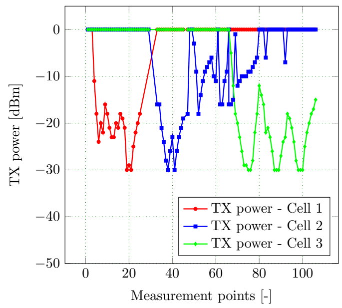
Two representative power allocation policies based on heuristic iterative search were implemented as part of the LSA controller: (i) “Derivative” algorithm and (ii) “Shannon” algorithm. Both methods assign the maximum allowed uplink power across the cells such that the total interference from the network towards the moving measurement cart (which represents the incumbent) does not exceed the given threshold. Our trial scenario utilizes four UEs; they remain stationary and their positions are known. The interference from a cell (eNB) can typically be approximated by the maximum interference from all the UEs in this cell. Hence, for the three utilized cells (see Fig. 4.7), the total interference on the measurement cart is estimated as a sum of the interference levels produced by the UEs closest to the cart, taken across all cells.



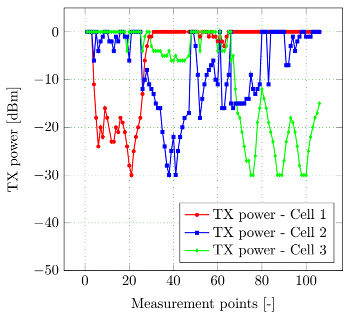
(a) Average/maximum interference for Derivative algorithm.



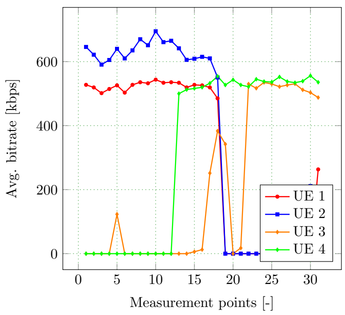
(b) Average/maximum interference for Shannon algorithm.



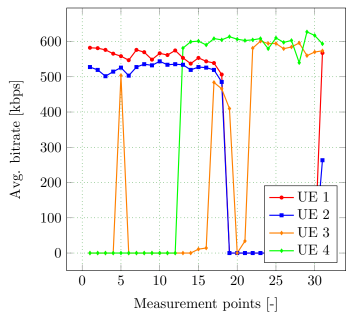
(c) Transmit power allocation for each cell according to Derivative algorithm.



(d) Transmit power allocation for each cell according to Shannon algorithm.



(e) Average bit-rate for deployed UEs (black path in Fig. 3).



(f) Maximum bit-rate for deployed UEs (black path in Fig. 3).

Fig. 4.8: Measurement-based results produced in the conducted dynamic LSA trial [218].

Derivative algorithm lowers the maximum allowed power across the cells in such a way that the decrease in interference per dB of power reduction is maximal. It chooses the cell in which the interfering UE is located closest to the cart and lowers the power in that cell – thus gaining the maximal loss in interference against the minimal loss in the overall power. If the power in a cell is reduced below its minimum feasible level, it is then shut down.

Shannon algorithm calculates the potential decrease in the total interference against the power reduction in each cell; then, using the capacity-estimation formula it also evaluates the changes in the user's effective transmission rate. Importantly, if the user's bit-rate is below its required value (subject to the current power restriction), there is no change in the effective transmission rate. Further, the algorithm selects the cell for power decrease to maximize the interference reduction subject to the minimal loss in the total effective transmission rate of its users. In effect, it attempts to maintain the UE connectivity to the cells instead of providing them with the highest reliability of the service. Therefore, this algorithm prioritizes keeping the users connected.

A user is considered to be connected if its effective bit-rate is higher than a certain threshold. Similar to Derivative algorithm, Shannon algorithm first lowers the power in the closest cell, thus reducing its interference towards the measurement cart, but only until the lowest transmission rate in this cell reaches the threshold. While the interference threshold is still not reached, the algorithm moves to the second closest cell. If the power level is such that the bit-rate of the "worst" UE has reached the threshold, but the interference still remains above the target value, the algorithm returns to the first closest cell, drops the "worst" user and again lowers the power in a similar manner, by comparing the second "worst" user's bit-rate against the threshold. Varying the transmission rate threshold, one can control the minimal guaranteed bit-rate. On the other hand, setting the threshold too high can cause more user drops from the network, since a UE is considered dropped when it cannot maintain its threshold bit-rate. Therefore, a sensible solution would be to set the QoS-guaranteed bit-rate equal to the threshold transmission rate [218].

Key Hands-on Observations

Our primary objectives in the conducted dynamic LSA trial were to (i) compare the above power allocation policies and (ii) verify whether the corresponding algorithms operate as intended, i.e., do not breach the interference threshold while meeting their respective optimization targets. The measurements were collected on a predetermined set of the measurement cart locations, see Fig. 4.7, where two evaluation scenarios are illustrated: (i) the black path indicates the measurements for the purposes of LSA assessment while (ii) the blue path stands for the overall testing of the implemented heuristic iterative search logic. Note that the system was notified on the movement of the measurement cart, while at every time instance the interference was recorded. All of the relevant data was continuously logged for further analysis. Accordingly, Fig. 4.8a and Fig. 4.8b report on the average (red line) and the maximum (blue line) interference levels received by the measurement cart at each position for both algorithms.

Comparing Fig. 4.8c and Fig. 4.8d, that illustrate the power allocated according to Derivative and Shannon algorithms respectively, one can observe, that when the cart is located in the first cell the Derivative algorithm only alters the power allocation there, while the Shannon algorithm adjusts all three cells in order to raise power and transmission rate in the closest cell. Hence, it can be concluded that Shannon algorithm operates more flexibly over the entire network, while Derivative algorithm mostly concentrates on the nearest cells. From Fig. 4.8a and Fig. 4.8b, where the average and the maximum interference received by the measurement cart across the check points are reported, we learn that unlike the Derivative algorithm the Shannon algorithm not only lowers the average interference, but also attempts to maintain it as close to the threshold as possible, so increasing power and transmission rate in the network.

Importantly, for most of the considered locations our implemented heuristic iterative search logic is ensuring that the interference threshold level is not breached. Further, analyzing the service rates displayed in Fig. 4.8e and Fig. 4.8f, we note that the cells can support the necessary data rates of 512 kbps for their cell-center UEs at any power level, until they have to be shut down. Clearly, the cell-edge UEs n.2 and n.3 suffer from less consistent service even when the cells remain up. However, we generally observe that while the iterative search logic may not always provide consistent performance, the interference received by the measurement cart in most of the cases remains below the defined threshold. This is true even when cells (Cell 1 and Cell 2) are turned on and the measurement cart is located directly between them [218].

4.2.5 Main Outcomes and Perspectives

This work accentuates the importance of highly dynamic spectrum sharing to leverage additional bandwidth that may be lightly used by its original incumbents. To further improve upon spectrum utilization in demanding 5G systems, we focus on the emerging LSA framework for vertical sharing, where the incumbent(s) and the licensee(s) operate over the same geographical area by utilizing common frequencies in a carefully controlled manner. This concept has been coined in 2013 and since then rapidly took flight with many hands-on demonstrations across Europe (see Fig. 4.9), primarily in 2016. Supported by visible research initiatives, such as ADEL [220] and CORE++ [222], [224], [226], the LSA functionality has been tested in a number of countries with the emphasis on the feasibility of its early implementation.

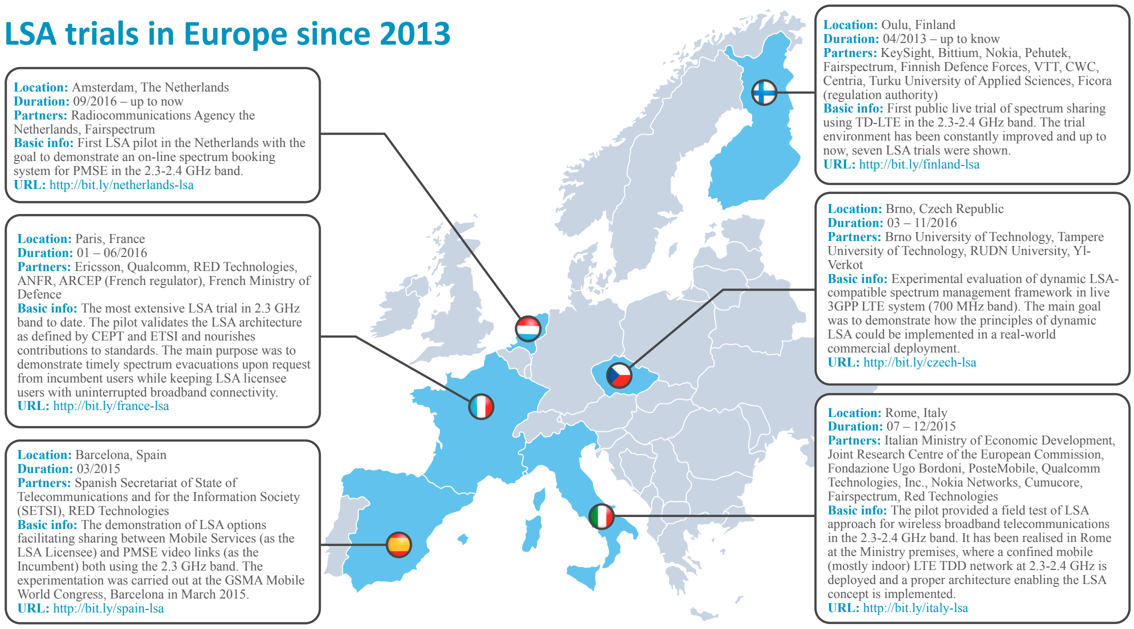


Fig. 4.9: Geography of existing LSA trials in Europe [218].

Complementing these important efforts, the present study relies on our rigorous past research[18] to advance the state-of-the-art on LSA by outlining its additional functionality required for highly dynamic operation. We therefore elaborate the key principles of system implementation as well as contribute our unique practical methodology based on a live

[18]Please, refer to a summary on our prior system-level evaluations of dynamic LSA operation here: http://winter-group.net/dyn-lsa-sim-res/

cellular network deployment. The obtained measurements support the rich capabilities of highly dynamic LSA operation in a commercial-grade network as well as report on the crucial performance indicators related to QoS and service reliability.

Going further, we believe that our results will become instrumental to fully reap the benefits of LSA-based highly dynamic spectrum management in 5G networks, whether in 2.3 – 2.4 GHz bands or at alternative frequencies, such as 3.4 – 3.8 GHz and possibly up to 4.2 GHz in perspective. This will require further demonstration efforts that may rely on our methodology proposed in this work, which could also be useful for other spectrum sharing initiatives across the globe, including Citizens Broadband Radio Service (CBRS) in the US as well as dynamic spectrum utilization at mmWave frequencies. Ultimately, our work advances the efficient utilization of LSA-based spectrum management at high granularity and facilitates its adoption in commercial cellular network deployments.

4.3 Transmit Power Reduction for a Typical Cell with LSA Capabilities

As it was thoroughly mentioned in previous section, a viable alternative to augment network capacity relatively quickly lies in the utilization of recently ratified Licensed Shared Access (LSA) regulatory framework [234]. In contrast to legacy spectrum management tools that require significant time to redistribute the radio frequencies, LSA enables more dynamic spectrum sharing between a limited number of participants [235]. Accordingly, there are three parties: the LSA licensee, the owner of the shared spectrum (named the incumbent), and the LSA controller [219]. The licensee (e.g., a network operator) can obtain a permission to operate on the shared LSA bands owned by an incumbent, while the LSA controller is responsible for ensuring that the conditions of the licensed spectrum usage are not violated by the licensee.

Therefore, the LSA controller may have access to the infrastructure of the mobile operator and take preventive measures. The key factor that can violate the LSA usage rules is uncontrolled interference produced by the LSA licensee towards the incumbent, which needs to be managed [236]. Here, one of the possible actions (named the LSA policies) by the controller is powering down the entire cell that causes the excessive interference to the spectrum owner. This is simple but inefficient in a way, that users of the operator's network are then forced to migrate to other frequencies. In case the user terminals are causing interference to the incumbent's systems, the mobile operator may prefer other methods to maintain the LSA agreement and at the same time avoid the unwanted user outage.

Along these lines, another LSA policy that does not disrupt user service, when satisfying the interference constraints of the spectrum owner, is known as "limit power" [228]. It effectively reduces the transmit power of the user terminals served on the LSA bands whenever requested by the incumbent's systems. This section contributes a novel mathematical evaluation of the transmit power reduction process as part of the 'limit power' operation in a representative LSA scenario by considering a typical operator's cell. We verify the obtained analytical findings for the user transmit power and the corresponding transmission rate with more detailed system-level simulations to confirm their accuracy. As a result, our model constitutes a simple estimate on the practical operation of a feasible LSA mechanism.

4.3.1 System Model for a Typical Network Cell

In this section, we model a representative dynamic LSA scenario, where the incumbent (i.e., the airport) owns a spectrum license across a certain geographical area [237] and utilizes the corresponding frequencies for the aircraft telemetry. In the same area, where the airplanes receive telemetry signals, a co-located cellular network is deployed and the respective mobile network operator (MNO) has the means to constrain the interference produced towards the aircraft. We also assume that the aircraft departures are only occasional, as is the case for smaller airports. This effectively means that at most one airplane is present within the MNO coverage at a particular time. As a result, the incumbent's spectrum is effectively used only in a relatively small and localized area around the aircraft [238].

In the considered scenario, the MNO (i.e., the LSA licensee) utilizes the incumbent's spectrum until an airplane needs to receive telemetry signals from the air traffic control. Whenever it happens, the cellular network restricts the interference that its served by UE (causes around the location of the aircraft), so as not to disrupt the telemetry signal. To this end, the MNO employs a 'limit power' policy, which reduces the power of the UEs served on the LSA bands in the target area. Table 4.3 introduces the notation utilized in what follows[19] [238].

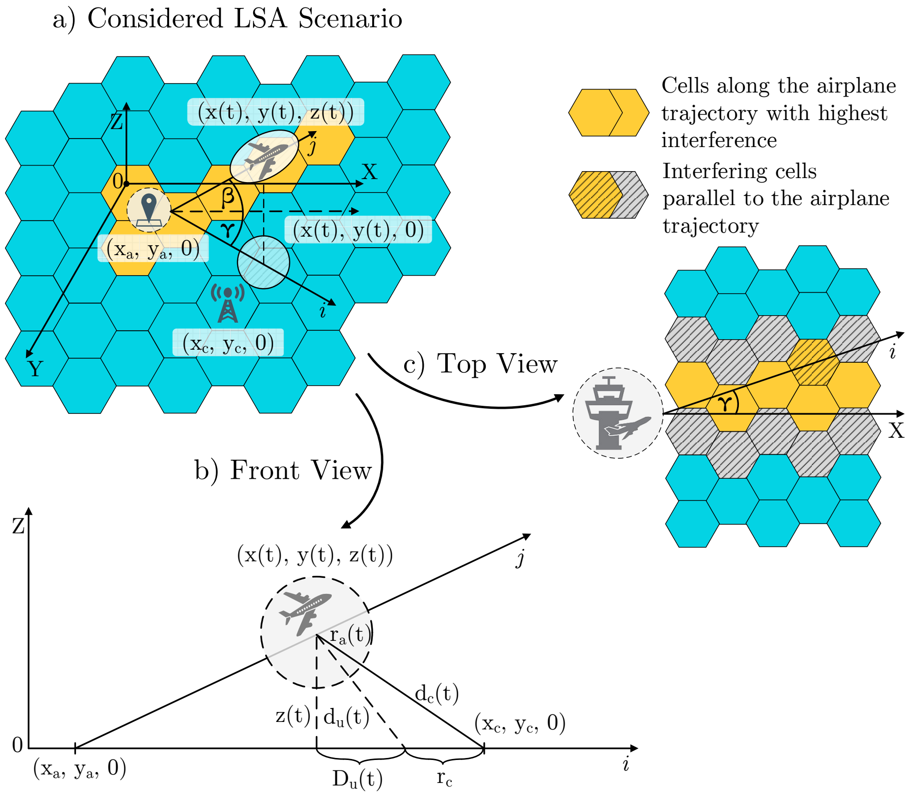


Fig. 4.10: Considered LSA-centric "airport" scenario [238].

In more detail, the airport is located at the coordinates (x_a, y_a) and has a transmitter that sends the telemetry signals to the airplanes during e.g., their take-off. The carrier frequency of the transmitter is denoted as f. The airplanes take off with the speed of v_0, the acceleration of a, and the ascending angle of β by following the trajectory j (see Fig. 4.10a). The runway faces along the vector i with the angle of γ towards the coordinate

[19]Note that c is used both as an index and as a separate parameter in some formulations. In case it is used as an index, it refers to the cell parameters; in case it is used as a separate parameter, it denotes the speed of light. Also note that while function $p_u(t)$ represents the reduced UE power, the constant p_u stands for the initial UE power.

grid x. The co-located cellular network utilizes the airport frequencies under the LSA rules. The tagged base station (eNodeB) has a directional transmitter that does not interfere with the signals that the aircraft receives from the airport. In contrast, the UEs have omnidirectional transmitters that operate at the power of p_u and can interfere with the airplanes in their vicinity.

We consider the worst-case scenario for a typical MNO cell, where the user interfering with the aircraft has a position in the cell that is the closest to the airplane. The target eNodeB is located at the coordinates (x_c, y_c), while the respective cell has the radius of r_c. The UE may interfere with the telemetry signal and the corresponding interference threshold is given by the value I_0. It means that if the interference $I(t)$ towards the airplane at time t reaches the threshold of I_0, the transmit power of the user will be reduced so that the interference towards the plane lowers down to this threshold. When the said interference eventually falls under the threshold value of I_0, the UE power can be restored.

Hence, we need to determine the time slot, when the cell interference towards the airplane causes interference in excess of the threshold I_0. Let the airplane be located at the coordinates $(x(t), y(t), z(t))$ at time t. Knowing its starting position together with other relevant parameters, one can model its location as:

$$x(t) = x_a + (v_0 t + \frac{at^2}{2} \cos\beta) \cos\gamma, \tag{4.3}$$

$$y(t) = y_a + (v_0 t + \frac{at^2}{2} \cos\beta) \sin\gamma, \tag{4.4}$$

$$z(t) = \frac{at^2}{2} \sin\beta. \tag{4.5}$$

We further denote the distance between the airplane and the eNodeB as

$$d_c(t) = \sqrt{(x(t) - x_c)^2 + (y(t) - y_c)^2 + z^2(t)}, \tag{4.6}$$

and the distance between the airplane and the closest cell-edge UE as

$$d_u(t) = \sqrt{(\sqrt{d_c^2(t) - z^2(t)} - r_c)^2 + z^2(t)}. \tag{4.7}$$

The above distances are indicated in Fig. 4.10b, which is a front view projection along the airplane's moving trajectory. The free-space path loss of the signal that travels the distance of d can be established by applying the formula

$$FSPL(d) = 20lg\left(\frac{4\pi f d}{c}\right), \tag{4.8}$$

where c is the speed of light. Using the variables as defined above, in what follows we formulate a feasible power reduction algorithm in terms of the network parameters [238].

Tab. 4.3: Utilized notation

Parameter	Value	Description
Airport-related parameters		
f	2.1 GHz	LSA carrier frequency
S	1 (Omnidir. antenna)	sectors/cell on the LSA band
v_0	63.88 m/s	airplane take-off speed
a	5 m/s^2	airplane acceleration
β	7 deg	airplane ascent angle
I_0	-90 dBm	interference threshold for the airplane over 10 MHz
free space		signal propagation model
γ	15 deg	take-off runway turn angle with x axis
$(x_a, y_a, 0)$	(0,0,0)	position of the airport
$(x(t), y(t), z(t))$		position of the airplane at time t
r_a		airplane radio 'shadow' radius
R_a		airplane radio 'shadow' radius projection onto vector i
Operator-related parameters		
F_op	2.4 GHz	MNO carrier frequency
S_op	3	sectors/cell on the MNO band
N_cell	25	number of cells
ISD	150 m	inter-site distance
r_c	288 m	cell radius
urban micro		signal propagation model for the network
hexagonal		cell shape
h_BS	10 m	cell tower height
h_UE	1.5 m	UE (user) height
p_u	24 dBm	initial UE power
$(x_c, y_c, 0)$		position of the tagged eNodeB
$I(t)$		interference received by airplane from the cell UE at time t
$d_c(t)$		distance between the airplane and the eNodeB at time t
$D_c(t)$		projection of the distance between the airplane and the eNodeB at time t onto plane XOY
$d(t)$		distance between the airplane and the closest UE at time t
$d_u(t)$		distance between the airplane and the closest edge UE at time t
$D_u(t)$		projection of the distance between the airplane and the closest edge UE at time t onto plane XOY
$p_u(t)$		reduced UE power at time t
C	20 MHz	channel bandwidth
w	16.8 Mbps	initial downlink transmission rate
$w(t)$		downlink transmission rate at time t

4.3.2 Modeling Transmit Power Reduction in LSA

Relying on the above introduced notation, we formulate a feasible algorithm to estimate the needed UE power reduction levels. The reference scenario, control objectives, and specific constants have been summarized in the previous section. First, by utilizing the expression 4.8, we can characterize the signal level from the UE as perceived by the airplane at time t as

$$I(t) = p_u(t) - FSPL(d(t)). \tag{4.9}$$

Further, from the expression (4.9), we can acquire the distance $d(t)$ in the form

$$d_u(t) = FSPL^{-1}\left(p_u(t) - I(t)\right) = \frac{c}{4\pi f} 10^{\frac{p_u(t)-I(t)}{20}}, \tag{4.10}$$

and since we consider the case where interference towards the airplane $I(t) = I_0$ to evaluate the radio 'shadow', $d_u(t) \equiv r_a(t)$. Hence, we can express the airplane's radio 'shadow' radius as

$$r_a = \frac{c}{4\pi f} 10^{\frac{p_u - I_0}{20}}. \tag{4.11}$$

As a result, we have obtained the maximum area around the airplane, interference from which can become in excess of the threshold I_0, that is, the radio 'shadow' radius. Let us further assess the time slot $[t_{in}, t_{out}]$, when the airplane can receive high enough interference from the cell. We denote the projections (see Fig. 4.10b) as

- $D_c(t) = \sqrt{d_c^2(t) - z^2(t)}$ is the projection of the distance from the airplane to the eNodeB onto vector i;
- $R_a(t) = \sqrt{r_a^2(t) - z^2(t)}$ is the projection of the airplane radio 'shadow' onto vector i;
- $D_u(t) = |D_c(t) - r_c|$ is the projection of the distance from the airplane to the cell-edge user onto vector i.

Note that we consider the moments of time when the airplane's radio 'shadow' enters and leaves the cell coverage area. Then, the time slot $[t_{in}, t_{out}]$ can be established as a positive solution to the following equation

$$D_c(t) = R_a(t) + r_c. \tag{4.12}$$

We note that if the above equation does not have positive solutions, it means that the airplane's trajectory lies far enough from the target cell and hence the UE signal level does not exceed the interference threshold. If the equation at hand has a single positive solution, then the airplane's radio 'shadow' only touches the cell in one point. In this case, the UE interference reaches the threshold, but does not exceed it. Therefore, if the radio 'shadow' does not cross the cell perimeter, there is no need to reduce the UE power. If the equation has one positive and one negative solution, then the airplane took off while its radio 'shadow' has already crossed the cell border, and thus we can assume $t_{in} = 0$. Further, we establish the distance between the airplane and the closest UE in the cell. There are three possible cases.

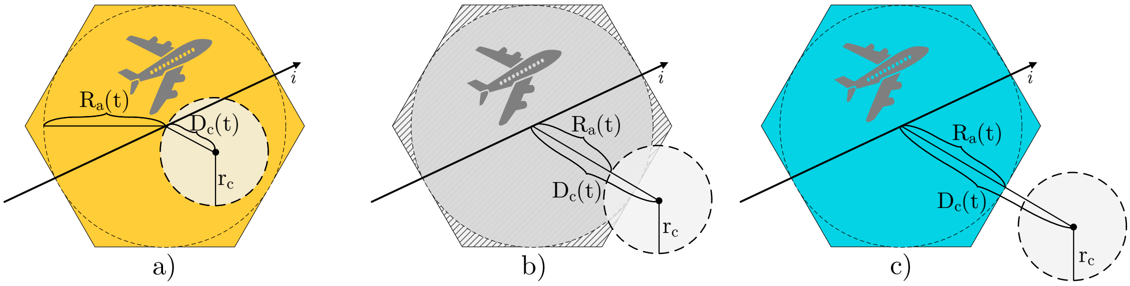


Fig. 4.11: Airplane positioning in relation to the cell: a) Above the cell; b) Close to the cell; c) Far from the cell [238].

Case A
When $D_c(t) \leq r_c$, that is, the airplane is located directly above the cell. In this case, since we consider the worst-case scenario, the closest UE is located directly below the airplane. Consequently, the distance between the airplane and the closest user equals the height of the flight, i.e., $d_u(t) = z(t)$ (Fig. 4.11a).

Case B
When $r_c < D_c(t) < R_a(t) + r_c$, that is, the airplane is located close enough to the cell to experience high interference, but not directly above the cell (Fig. 4.11b). In this case, the distance between the airplane and the closest user in the worst case equals the distance between the airplane and the cell edge $d(t) = d_u(t)$.

Case C
When $R_a(t) + r_c \leq D_c(t)$, that is, the airplane's trajectory lies far enough from the cell. In this case, the interference that the airplane receives from the cell does not exceed the threshold (Fig. 4.11c).

It can be observed that in cases B and C the distance to the closest UE is calculated with the same expression. However, in case C, the interference from the target user does not lead to a decrease in the transmit power. Therefore, we can obtain the distance to the closest UE as follows

$$d(t) = \begin{cases} z(t), & D_c(t) \leq r_c, \\ d_u(t), & r_c < D_c(t). \end{cases} \tag{4.13}$$

Considering the time slot in question, $[t_in, t_out]$, we can now calculate the interference for each moment of time within this time slot as

$$I(t) = \begin{cases} p_u(t) - FSPL\left(d(t)\right), & t \in [t_{in}, t_{out}], \\ I_0, & t \notin [t_{in}, t_{out}]. \end{cases} \tag{4.14}$$

As a result, by utilizing the expression (10) with the interference threshold of I_0 as well as by using the expressions (6) and (7), we can quantify the UE power reduction level $p_u(t)$ as follows

$$p_u(t) = \begin{cases} I_0 + FSPL(d_u(t)), & t \in [t_{in}, t_{out}], \\ p_u, & t \notin [t_{in}, t_{out}]. \end{cases} \tag{4.15}$$

Consequently, we can employ e.g., the Shannon's formula to calculate the maximum downlink (DL) transmission rate in the cell as

$$w(t) = C \cdot ln\left(1 + 10^{\frac{p_u(t) - FSPL(r_c) - I}{10}}\right), \tag{4.16}$$

where the interference towards the user signal I can be considered constant, which is produced by using the initial DL transmission rate as

$$I = p_u - FSPL(r_c) - 10lg\left(e^{\frac{w}{C}} - 1\right). \tag{4.17}$$

Finally, we can rewrite the expression (4.16) in the form

$$w(t) = C \cdot ln\left(1 + 10^{lg\left(e^{\frac{w}{C}} - 1\right) - \frac{p_u - p_u(t)}{10}}\right). \tag{4.18}$$

4.3.3 Numerical Case Study

In this section, we offer a numerical evaluation for several reference use cases. The input data is summarized in Table 4.3 and the base station (eNB) locations are displayed in Fig. 4.10c. First, we verify our below analytical results with system-level simulations inside a multi-cell environment created by our detailed simulation framework [239], which was calibrated against the reference data for 3GPP LTE [240]. To this end, Fig. 4.12 indicates a close match with a minor difference in the results due to additional features, such as admission and power control, taken into account by the simulations.

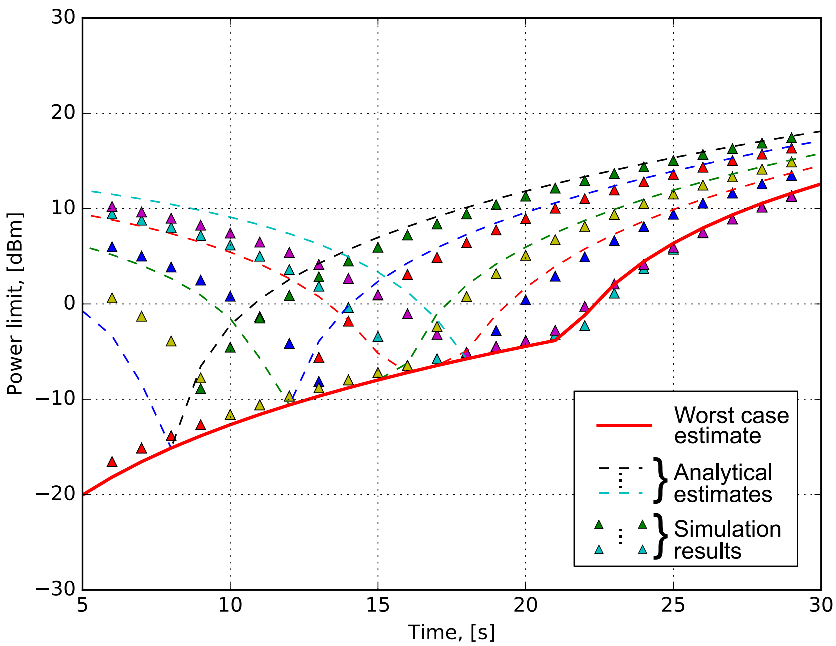


Fig. 4.12: Transmit power in cells along the airplane's trajectory [238].

As a consequence, the transmit power is slightly different for our analytical model, because in simulations the power control algorithm attempts to maintain the SINR values closer to a certain target value (i.e., SINR-target power control). The resulting transmit power depends on many practical factors, including the path loss model, the deployment parameters, and the distance between cells. However, even with the simplifying assumptions adopted by our analytical model, we observe that the key performance indicators demonstrate close correspondence.

In particular, the performance results for both analytical and simulation models are brought together in Fig. 4.12. Here, the dashed curves represent the analytical values and markers illustrate the respective simulation data, while the solid curve is the analytical worst-case transmit power across all of the cells. We note that our constructed analytical model can serve as a tight estimate on the simulation results as can also be confirmed by the worst-case results, where the solid curve closely follows the one obtained with simulations. In the sequel, we therefore primarily rely on our verified analytical model.

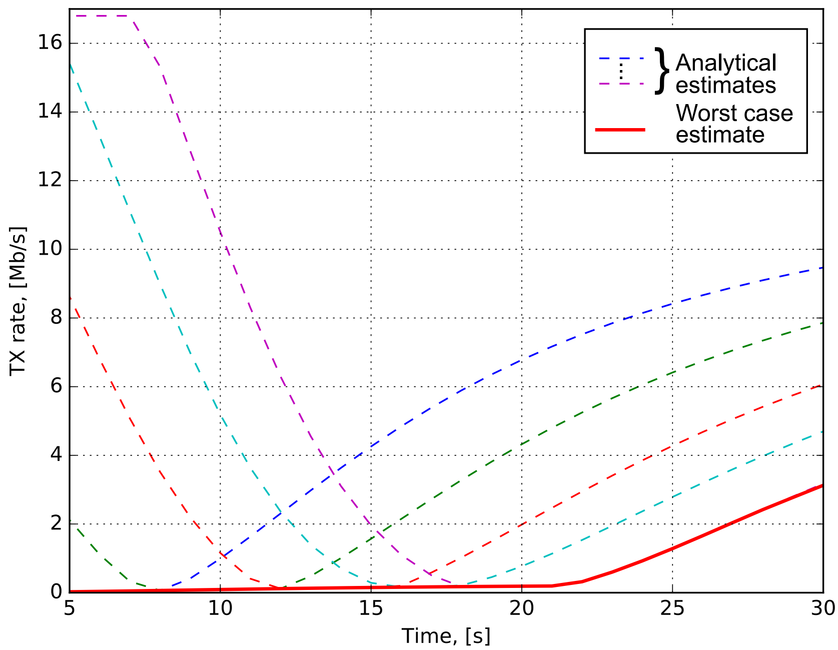


Fig. 4.13: DL transmission rate in cells along the trajectory [238].

To this end, Fig. 4.12 and Fig. 4.13 demonstrate the case, when the cells are located directly along the airplane's path and thus produce the highest interference towards the airplane (see highlighted yellow cells in Fig. 4.10c). For most of these cells, the airplane is located directly above them at a certain moment of time (Case A (4.3.2)). To this end, Fig. 4.12 and Fig. 4.13 report on the UE transmit power and DL transmission rate for different cells along the airplane's trajectory. The dashed curves correspond to the transmit power and DL transmission rate variation for each marked cell, while the solid curve outlines the minimal possible values across all of the cells as the worst case.

It can be observed that both transmit power and transmission rate decrease rapidly when the airplane's radio 'shadow' enters the cell. Then, they grow steadily as the airplane travels directly above the deployment from the moment it enters the cell to the moment it leaves it. This growth is because the airplane is gaining height and thus the interfering signal from the cells is decreased. Whenever the airplane leaves the cell's coverage area, the distance to the cell increases further, which brings both transmit power and transmission rate back to their regular values.

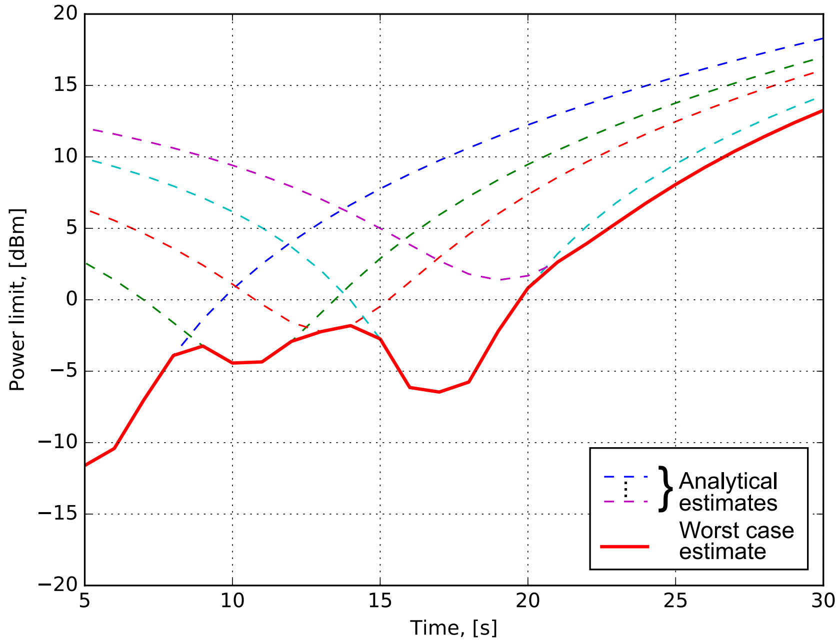


Fig. 4.14: Transmit power in cells parallel to the trajectory [238].

Further, we consider a scenario where the cells are located in the same pattern, but are shifted one cell up as illustrated in Fig. 4.10c with black hatching, Fig. 4.14 and Fig. 4.15. In this scenario, primarily cases B (4.3.2) and C (4.3.2) take effect. We note that in contrast to the previous scenario, where the cells are located along the airplane's trajectory, here the minimum transmission rate is relatively higher. This is because the cells in question are located farther away from the airplane's trajectory, even though the values do not change much across the cells. This effect is due to the fact that the considered cells are located in close proximity to the airplane's trajectory.

Here, the plots for the transmit power report that its worst-case value in these cells is almost twice as high as that for the cells that are directly along the trajectory, whenever the airplane is close to the considered cells. It can be emphasized that at $t > 25$ both plots resemble the respective pots for the cells along the airplane's trajectory. It occurs because the airplane leaves the coverage and gains significant height, hence effectively reducing the difference between distances to the cells along its trajectory as well as those to the cells in question, which are parallel to its course.

4.3.4 Lessons Learned and Conclusions

In this section, we studied a typical cell scenario under the 'limit power' policy by capturing the produced interference as the key parameter in the cellular network that employs LSA

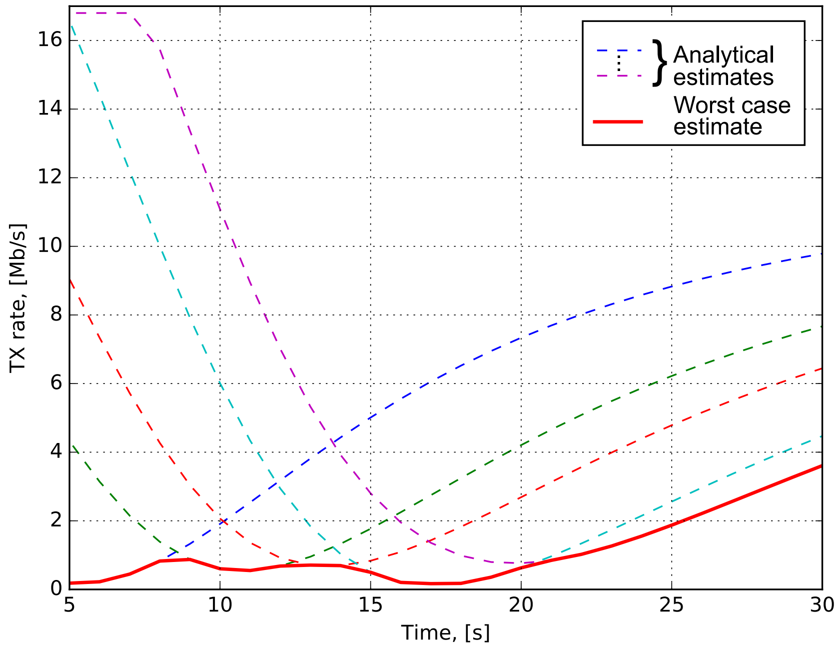


Fig. 4.15: DL transmission rate in cells parallel to the trajectory [238].

mechanisms. Our numerical analysis reveals that the UE transmit power and the DL transmission rate are minimal for those cells along the airplane's trajectory, whose centers are positioned directly under the airplane. However, for the cells located farther away from the airplane the worst case values are reached for the cells that are the closest to its trajectory. More specifically, we demonstrated that the intervals of sharp transmit power reduction are comparatively short for each cell, while the power reaches its regular value once the airplane leaves the cell coverage. Our analytical results are verified by system-level simulations and in practice can serve as a tight performance estimate.

5 CONCLUDING SUMMARY

Rapid penetration of wireless connectivity, almost exponential increase in wireless data (multimedia) usage and proliferation of feature-rich smart devices are gradually setting the stage for next major cellular evolution towards 5G. Next-generation (5G) wireless systems are already promising a manifold increase in data rate, ubiquitous connectivity, Quality of Service, and Quality of Experience. A plethora of new applications, like Machine-to-Machine communication, Internet of Things, Tactile Internet, Augmented and Virtual reality, and Smart Grids are expected to be supported under the umbrella of 5G wireless communication systems.

The mobile networks in the 5G era are comprehensively described in the Chapter 2, where a wide variety of new emerging 5G applications (substantiating the commercial roll out of 5G wireless systems) are discussed thoroughly. Having summarized the key requirements given by the 5G applications, the second part of the Chapter 2 details the 5G technology enablers. To provide the complete picture, this part is further divided to: (i) 5G radio access network enablers (containing both, Radio Access Technology and Radio Access Network parts of the 5G access network i.e., Massive MIMO, Device-to-Device communication, millimeter wave technology, Licensed Shared Access and Radio Access Network as a Service), and (ii) 5G core networks enablers, which are pertinent to support the above 5G RAN enablers i.e., Software Defined Networks and Network Function Virtualization.

At the length of this dissertation thesis, author has focused on two promising research areas targeting the research questions connected with the lack of bandwidth: (i) proximity-based (cellular-assisted) networking (Chapter 3), and (ii) dynamic allocation of spectrum resources (Chapter 4). Both chapters are structured with the goal to provide at the first the problem statement followed by the design of proposed novel mechanisms (communication principles), targeting to reach the requirements given by the upcoming 5G applications and the **comprehensive evaluation of implemented principles within the experimental LTE deployment at Brno University of Technology, Czech Republic.**

As the direct communication was recognized as the one of the key communication mechanisms to provide end users with the virtually unlimited capacity and ubiquitous coverage introducing the "anytime & anywhere" connectivity, the proximity-based (cellular-assisted) networking is detailed within the Chapter 3. This novel form of networking is enabled by D2D communication between / among the laptops, smartphones, and wearables of people in proximity of each other. Unfortunately, it has remained limited by the fact that most people are simply not aware of the many potential virtual opportunities in their proximity at any given time. This is complemented by the topical digital privacy and security concerns surrounding direct communication between "stranger's" devices. Fortunately, these concerns can be mitigated with the help of a centralized trusted entity, such as a cellular service provider, which can not only authenticate and protect the privacy of devices involved into D2D communication, but also facilitate the discovery of device capabilities and their available content. Based on the above, Chapter 3 offers an extensive research work behind this type of “cellular-assisted” D2D communication, detailing the key aspects of this technology as well as its implementation, relevant usage scenarios, security challenges, and user experience observations from large-scale LTE deployment located at Brno University of Technology. With the proposed novel prototype implementation, current 3GPP LTE networks may supply mobile devices with effective means to discover, connect, and communicate with their desired proximal partners over high-rate WiFi-Direct channels. What is even more important, such connectivity can be made seamless and automatic, taking advantage of reliable, secure, and optimized direct links. **As a main output of this particular research (Chapter 3), the obtained findings (supported by the realized 3GPP LTE-Assisted Wi-Fi Direct trial implementation[20]) were included as a part of the 3GPP Release 12 specification [241].**

Chapter 4 further builds on the studied requirements given by the upcoming 5G applications, when the attention is given to the dynamic allocation of spectrum resources. First part of the fourth chapter is dedicated to a practical evaluation of RAN modeling in indoor LTE deployment, where we benefit from the full access to the real LTE-A deployment and complete building documentation. The measured values of Signal to Interference plus Noise Ratio and network throughput are compared with the results from the novel radio signal propagation model, implemented in Python. The obtained values are in consequence used for the transmission power configuration to realize the coverage and capacity optimization in cellular systems. In the process of configuration the TX power optimization mechanism, a number of challenges regarding the used LTE-A deployment have been addressed. As mentioned at length in the Chapter 4, utilized LTE test-bed is provided by Huawei company. **Since the configuration procedure highly depends on the vendor (Huawei, Ericsson, etc.), we primarily aimed to identify key elements of TX power management mechanisms, which are common for all LTE deployments.**

The second part of the Chapter 4 deals with the thorough description of the 5G-Ready Highly Dynamic Spectrum Management with LSA framework. Despite decisive progress in many enabling solutions, fifth-generation cellular deployments may still suffer from a glaring lack of bandwidth due to inefficient utilization of radio spectrum resources, which calls for immediate action. To this end, several capable frameworks have recently emerged to help the mobile network operators leverage the abundant frequency bands that are lightly utilized by other incumbents. The recent Licensed Shared Access regulatory framework allows for controlled sharing of spectrum between the incumbent and licensee, such as the MNOs, which coexist geographically. This powerful concept has been subject to several early technology demonstrations that confirm its implementation feasibility. However, the full potential of LSA-based spectrum management can only become available if it is empowered to operate dynamically and at high space-time-frequency gran-

[20]http://wislab.cz/our-work/lte-assisted-wifi-direct

ularity. Complementing the prior efforts, in this work, the functionality that is required by the LSA system to achieve the much needed flexible operation as well as report on the results of respective live trial that employs a full-fledged commercial-grade cellular network deployment is detailed. **Obtained practical results (supported by a novel mathematical analysis of the LSA policy in a characteristic scenario featuring a highly-dynamic incumbent (the airport)) become instrumental to facilitate more dynamic bandwidth sharing and thus promise to advance on the degrees of spectrum utilization in future 5G cellular systems without compromising the service quality of their users.**

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LIST OF SYMBOLS, PHYSICAL CONSTANTS AND ABBREVIATIONS

1G	1st Generation of Mobile Networks
2G	2nd Generation of Mobile Networks
3G	3rd Generation of Mobile Networks
3GPP	3rd Generation Partnership Project
4G	4th Generation of Mobile Networks
5G	5th Generation of Mobile Networks
AAA	Authentication, Authorization, Accounting
AI	Artificial Intelligence
ANDSF	Access Network Discovery and Selection Function
AP	Access Point
API	Application Programming Interface
AR	Augmented Reality
ASA	Authorized Shared Access
BAN	Body Area Network
BBU	Base Band Unit
BS	Base Station
BUT	Brno University of Technology
CA	Certificate Authority
CAPEX	Capital Expenditures
CBR	Constant Bit-Rate
CBRS	Citizens Broadband Radio Service
CCO	Coverage and Capacity Optimization
CEPT	Conference Europeenne des Postes et des Telecommunications
CR	Cognitive Radio
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
D2D	Device-to-Device
DL	Downlink
DR	Demand-Response
DUDe	Downlink and Uplink Decoupling
EC	European Commission
EDGE	Enhanced Data rates for GSM Evolution
eMBB	enhanced Mobile Broadband
eNB	evolved NodeB
EPC	Evolved Packet Core
eSMLC	evolved Serving Mobile Location Centre
ETSI	European Telecommunications Standards Institute
FDD	Frequency Division Duplex
GPRS	General Packet Radio Service

GPS	Global Positioning System
GSM	Global System for Mobile Communications
H2H	Human-to-Human
HARQ	Hybrid Automatic Repeat Request
HetNets	Heterogeneous Networks
HSPA	High Speed Packet Access
ID	Identifier
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IFOM	IP Flow Mobility
IMS	IP Multimedia Subsystem
IoE	Internet of Everything
IoT	Internet of Things
IoV	Machine-Type Communication Gateway
IP	Internet Protocol
IPv4	Internet Protocol Version 4
IPv6	Internet Protocol Version 6
IS	Information Security
ISM	Industrial, Scientific and Medical
ISMP	Inter-system Mobility Policy
ISRP	Inter-system Routing Policy
ITS	Intelligent Transportation Systems
ITU	International Telecommunication Union
KPI	Key Performance Indicator
LAA	Licensed Assisted Access
LAN	Local Area Network
LENA	LTE-EPC Network Simulator
LIPA	Local IP Access
LOS	Line-of-Sight
LPWAN	Low-Power Wide Area Networks
LSA	Licensed Shared Access
LTE	Long Term Evolution
LTE-A	LTE Advanced
LTE-M	LTE Machine-to-Machine
LTE-U	LTE Unlicensed
M2M	Machine-to-Machine
MAC	Medium Access Control
MADNET	Metropolitan Advanced Delivery Network
MAPCON	Multiple Access PDN Connection
MCS	Modulation and Coding Scheme
MIMO	Multiple-Input Multiple-Output

MME	Mobile Management Entity
mmWave	Millimeter Wave
MNO	Mobile Network Operator
MPTCP	Multipath Transmission Control Protocol
MTC	Machine-Type Communication
MTCD	Machine-Type Communication Devices
MTCG	Machine-Type Communication Gateway
NAS	Non-Access Stratum
NB-IoT	NarrowBand IoT
NFV	Network Function Virtualization
NLOS	Non-Line-of-Sight
Non-3GPP	Non Third Generation Partnership Project
NS-3	Network Simulator 3
OFDMA	Orthogonal Frequency-Division Multiple Access
OPEX	Operating Expenditures
OS	Operating System
P2P	Peer-to-Peer
PDN	Packet Data Network
PDSCH	Physical Downlink Shared Channel
PGW	PDN Gateway
PHY	Physical Layer
PKI	Public Key Infrastructure
PoC	Proof of Concept
ProSe	Proximity Services
PSK	Pre-Shared Key
QoS	Quality of Service
QoE	Quality of Experience
RA	Random Access
RACH	Random Access Channel
RAN	Radio Access Network
RANaaS	Radio Access Network as a Service
RAT	Radio Access Technology
RCS	Rich Communications Services
RFID	Radio Frequency Identification
RRC	Radio Resource Control
RRU	Remote Radio Unit
RSA	Rivest, Shamir, Adleman public-key cryptosystem
RSPG	Radio Spectrum Policy Group
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indicator

RTT	Round Trip Time
SCTP	Stream Control Transmission Protocol
SDN	Software Defined Networks
SGs	Smart Grids
SGW	Serving Gateway
SIM	Subscriber Identity Module
SINR	Signal to Interference plus Noise Ratio
SIPTO	Selected IP Traffic Offload
SLS	System Level Simulator
SMLC	Serving Mobile Location Centre
SNR	Signal-to-Noise Ratio
SON	Self-Organizing Network
SUPL	Secure User Plane Location
TA	Trusted Authority
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TI	Tactile Internet
TOMP	Traffic Offloading with Movement Prediction
TV	Television
TX	Transmission Power
UDP	User Datagram Protocol
UE	User Equipment
UGW	Unified Gateway
UL	Uplink
UMTS	Universal Mobile Telecommunication System
URLLC	Ultra-Reliable and Low Latency Communications
V2V	Vehicle-to-Vehicle
VLC	Visible Light Communication
VNI	Visual Networking Index
VoIP	Voice over IP
VoLTE	Voice over LTE
VR	Virtual Reality
WCDMA	Wideband Code Division Multiple Access
WFD	WiFi Direct
WGFM	Frequency Management Working Group
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WPA2	Wi-Fi Protected Access 2
WSN	Wireless Sensors Network

LIST OF APPENDICES

A APPENDIX

A.1 5G Related Activities in Europe

Tab. A.1: 5G related activities in Europe

Research Project / Research Groups	Reasearch Area
5GNOW (5th Generation Non-Orthogonal Waveforms for asynchronous signaling)	Non-orthogonal waveforms
5G PPP (5G Infrastructure Pblic Private Partnership)	Next generation of communication networks, ubiquitous super-fast connectivity
COMBO (COnvergence of fixed and Mobile BrOadband access / aggregation networks)	Fixed / Mobile Converged (FMC) broadband access / aggregation networks
iJOIN (Internetworking and JOINt Design of an Open Access and Backhaul Network)	RAN-as-a-Service, radio access based upon small cells, and a heterogeneous backhaul
MAMMOET (MAssive MiMO for Efficient Transmission)	Massive MIMO
METIS (Mobile and wireless communications Enablers for Twenty-twenty (2020) Information Society)	Provide a holistic framework 5G system concept
MCN (Mobile Cloud Networking)	Mobile Network, Decentralized Computing, Smart Storage
MOTO (Mobile Opportunistic Traffic Offloading)	Traffic offloading architecture
PHYLAWS (PHYsical Layer Wireless Security)	Security approaches for handsets and communications nodes
TROPIC (Traffic Optimization by the Integration of Information and Control)	Femtocell networking and cloud computing
University of Surrey 5G Innovation Centre (5GIC)	Lowering network costs, Anticipating user data needs to pre-allocate resources, Dense small cells, Device-to-device communication, Spectrum sensing (for unlicensed spectrum)
Sources: [75], [99], [242], [243], [244], [245], [246]	

A.2 Evolution of Wireless Technologies

Tab. A.2: Evolution of wireless technologies

Generations	Access Technology	Data Rate	Frequency Band	Bandwidth	Forward Error Correction	Switching	Applications
1 G	Advanced Mobile Phone Service (AMPS); Frequency Division Multiple Access (FDMA)	2.4 kbps	800 MHz	30 KHz	NA	Circuit	Voice
2 G	Global Systems for Mobile communications (GSM); Time Division Multiple Access (TDMA)	10 kbps	850/900/ 1800/ 1900 MHz	200 KHz	NA	Circuit	Voice+Data
	Code Division Multiple Access (CDMA)	10 kbps		1.25 MHz			
2.5 G	General Packet Radio Service	50 kbps		200 KHz		Circuit/ Packet	
	Enhanced Data Rate for GSM Evolution (EDGE)	2300 kbps		200 KHz			
3 G	Wideband Code Division Multiple Access (WCDMA) / Universal Mobile Telecommunications Systems (UMTS)	384 kbps	800/850/ 900/1800/ 1900/ 2100 MHz	5 MHz	Turbo Codes	Circuit/ Packet	Voice + Data + Video Calling
	Code Division Multiple Access (CDMA) 2000	384 kbps		1.25 MHz			
3.5 G	High Speed Uplink/Downlink Packet Access (HSUPA/HSDPA)	5-30 MHz		5 MHz		Packet	
	Evolution-Data Optimized (EVDO)	5-30 MHz		1.25 MHz			
3.75 G	Long Term Evolution (LTE); Orthogonal/Single Carrier Frequency Division Multiple Access (OFDMA/SC-FDMA)	100-200 MHz	1.8 GHz, 2.6 GHz	1.4 MHz to 20 MHz	Concatenated codes	Packet	Online Gaming + High definition television
	Worldwide Interoperability for Microwave Access (WiMAX); Scalable Orthogonal Frequency Division Multiple Access (SOFDMA)		3.5 GHz and 5.8 GHz initially	3.5 MHz and 7 MHz in band 3.5GHz; 10 MHz in band 5.8 GHz			
	Fixed WiMAX						
4 G	Long Term Evolution Advanced (LTE-A); Orthogonal / Single Carrier Frequency Division Multiple Access (OFDMA/SC-FDMA)	DL 3 Gbps UL 1.5 GHz	1.8 GHz, 2.6 GHz	1.4 MHz to 20 MHz	Turbo codes	Packet	Online gaming + High definition television
	Worldwide Interoperability for Microwave Access (WiMAX); Scalable Orthogonal Frequency Division Multiple Access (SOFDMA)	100-200 MHz	2.3 GHz, 2.5 GHz, and 3.5 GHz initially	3.5 MHz, 5 MHz, 7 MHz, 10 MHz and 8.75 MHz initially			
	Mobile WiMAX						
5 G	Beam Division Multiple Access (BDMA) and Non- and quasi-orthogonal or Filter Bank multi carrier (FBMC) multiple access	10-50 Gbps (expected)	1.8 GHz, 2.6 GHz and expected 30-300 GHz	60 GHz	Low Density Parity Check Codes (LDPC)	Packet	Ultra High definition video + virtual reality applications

Sources: [7], [9], [247], [248], [249]

A.3 Key Enablers for the Emerging 5G Wireless Systems

Tab. A.3: Key differentiators (enablers) for the emerging 5G wireless systems

Scenarios	Limitations of Legacy Network and What the 5G offers?
D2D communication	Limitations of Legacy Network
	Add-on technology thus requires higher computational overhead
	Multiple wireless hops entails a multifold waste of signaling resources as well as higher latency
	Requires mitigation of potential interferences between two communication links
	What 5G offers?
	Native support in 5G wireless systems
	Infrastructure centric communications utilize base stations, while ad-hoc (D2D) communications focuse on local data traffic
	5G wireless devices are expected to handle local traffic directly instead of relying data through a base station
	Beam-forming directive antennas offer to mitigate interferences between two communication links
M2M communication	Limitations of Legacy Network
	Legacy network typically operate with a few hundred devices per base station
	Not designed for M2M envisions of massive number of connected devices
	Low latency and real-time operation are stringent requirements for critical applications e.g., healthcare
	Small data blocks transmitted infrequently from diverse set of devices - different from current communication scenarios
	Control and channel estimation from massive diverse devices would add immense overheads in legacy network.
	What 5G offers?
	New mm-Wave spectrum can easily accommodate proliferation of devices
	Low latency in one of the key 5G requirements - enable to resolve time critical issues
	Non orthogonality and new waveforms could potentially answer sporadic traffic pattern
	C-RAN and SDN architecture relaxed tight coupling between the data and control planes
	Native support in 5G wireless
Internet of Things	Limitations of Legacy Network
	In traditional ubiquitous computing, only a limited number of sensors/actuators are connected to the applications
	However, IoT envisions connection of billions of sensors over the Internet
	Understanding received data and interpreting it automatically is challenging task
	IoT application domains and their implementation in current networks is hard to reach
	Security, privacy, and trust increase the IoT challenge significantly in current communication scenarios
	What 5G offers?
	5G offers paradigm shift in architecture, multiplexing and networking
	Extended coverage, higher throughput and lower latency
	Connection density of 1000x bandwidth per unit area, and 10-100x number of connections
Internet of Vehicles	Limitations of Legacy Network
	Complexity of distributed control of hundreds of thousands of cars is taken as a serious challenge
	The communications must be secured and fast to prevent disasters
	Current processing environment lacks swiftness, dedicated spectrum, intelligence and learning capabilities
	What 5G offers?
	Small cell site specific environment
	Offers dedicated links, cloud capabilities, content-centric networking and low latency commitments
Smart Homes, Smart Cities, Smart Grids	Limitations of Legacy Network
	Smart homes, smart cities and smart grids increase dense and diverse connectivity
	Supporting this rapid increase in data usage and connectivity represents extremely daunting task in 4G systems
	What 5G offers?
	The main differences in 5G (compared to 4G) would be greater spectrum availability at untapped mm-Wave spectrum
	Highly directional beam-forming antennas, longer battery life, reduced outage probability
	Greater bit rates in larger parts of coverage area, lower infrastructure costs.
	Higher cumulative capacity for many simultaneous users in both unlicensed and licensed spectrum
	Capabilities to address enormous data rates and connectivity in smart cities, homes and grids
Sources: [7], [75], [83], [86], [103]	

A.4 Full D2D protocol signaling

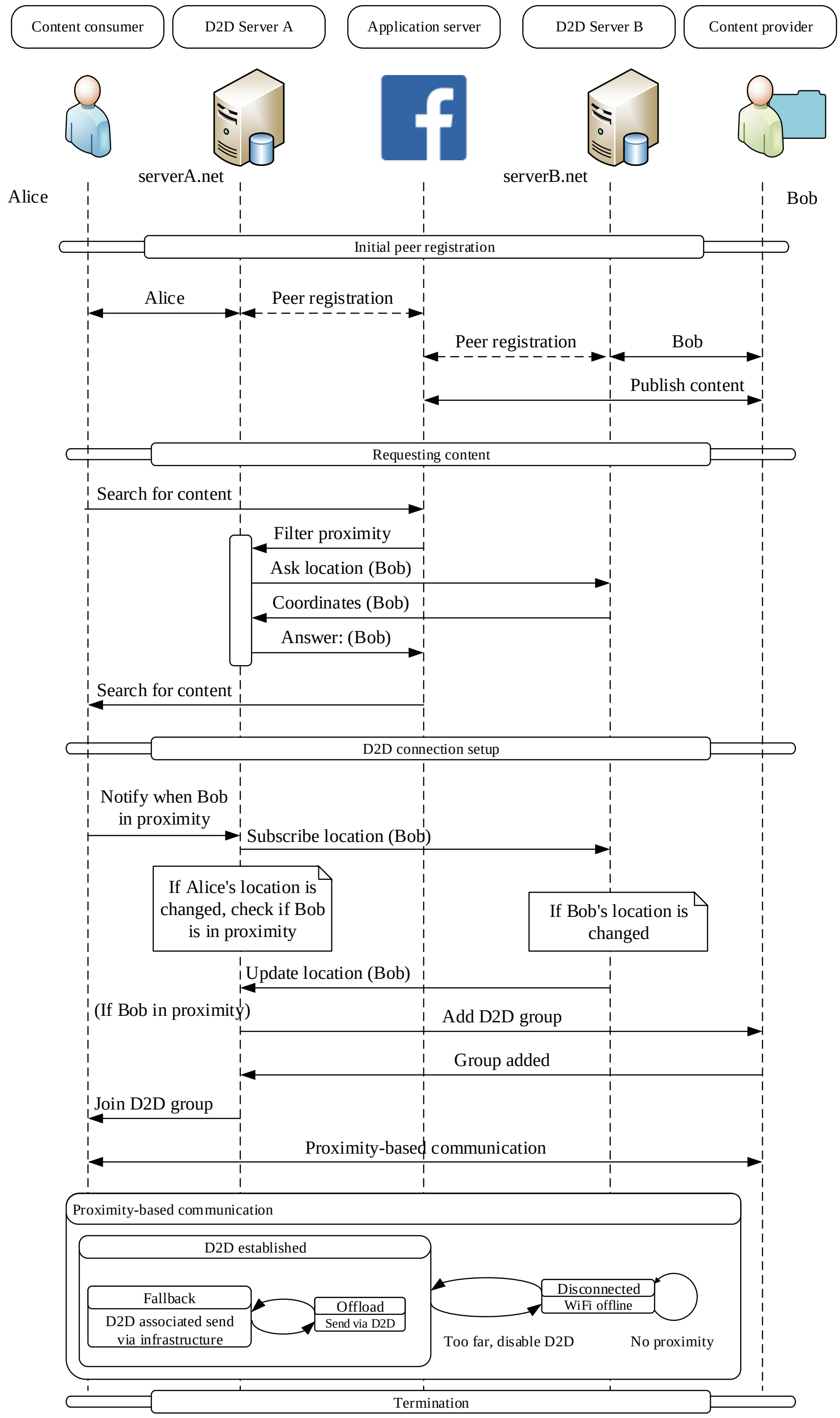

Fig. A.1: Considered D2D protocol signaling including all stages required for proximity discovery, D2D link establishment, and termination – detailed version [34].

A.5 Architecture of the envisioned D2D offload system

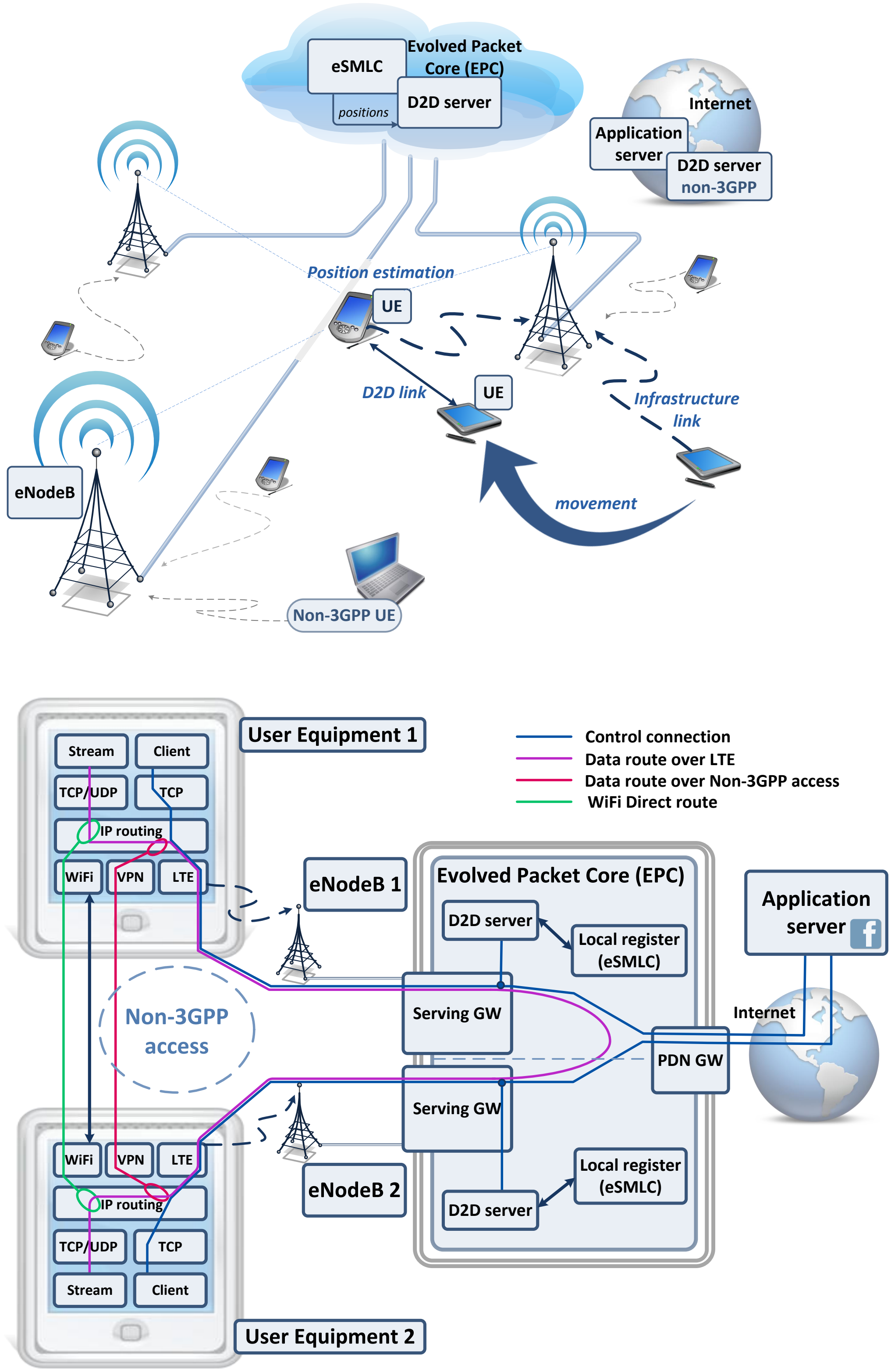

Fig. A.2: Architecture of the envisioned D2D offload system [34].

Curriculum Vitae

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	`https://www.linkedin.com/in/pavel-ma%C5%A1ek-40902b7a/`

QUALIFICATION AND PROFESSIONAL CAREER

Current position

2013–up to now	Junior researcher with the Department of Telecommunications, Faculty of Electrical Engineering and Communication (FEEC), Brno University of Technology (BUT)

Qualification

2013–2017 (planned)	Ph.D. in Teleinformatics, BUT, Doctoral thesis: *Heterogeneous Connectivity of Mobile Devices in 5G Wireless Systems*
2011–2013	MSc. in Telecommunication and Information Technology, BUT, Diploma thesis: *QoS model for mobile Ad-hoc network*
2008–2011	Bc. in Teleinformatics, BUT, Bachelor thesis: *IP Television*
2004–2008	Secondary Technical School - Jihlava, Branch: *Computer systems*

Professional career

2013–up to now	Member of the research group WISLAB (Wireless System Laboratory of Brno) Link: `http://www.wislab.cz`
2013–up to now	Junior researcher within the SIX Research Centre Link: `http://www.six.feec.vutbr.cz/`

PROFESSIONAL ACTIVITIES

Specialization	Research and development in the area of wireless networks, Machine-to-Machine (M2M), Human-to-Human (H2H) communication, Industry 4.0, next-generation (5G) networks, Internet of Things (IoT), heterogeneous networking, and data offloading techniques
	Author / co-author of products developed within the contractual research for premier ICT companies (Telekom Austria Group, etc.)
Scientific internships	Tampere University of Technology, Tampere, Finland, Ph.D. exchange stay; (08/2014 – 12/2014)
	Tampere University of Technology, Tampere, Finland, Ph.D. exchange stay; (10/2015 – 11/2015)
	Tampere University of Technology, Tampere, Finland, Ph.D. exchange stay; (09/2016 –10/2016)

Membership in scientific and technical program committee international conferences	International Congress on Ultra-Modern Telecommunications and Control Systems – ICUMT (workshop chair, 2015 – up to now) INternet of THings and ITs ENablers – INTHITEN 2016 (TPC member, 2015 – up to now)

Designated reviewer

• International Conference on Telecommunications and Signal Processing (WoS/Scopus, Conference)
• International Congress on Ultra Modern Telecommunications & Control Systems (WoS/Scopus, Conference)
• International Conference on Next Generation Wired/Wireless Advanced Networks and Systems (WoS/Scopus, Conference)
• International Journal of Advances in Telecommunications, Electrotechnics, Signals and Systems (Journal; ISSN: 1805-5443)
• IEEE Wireless Communications Letters (IF: 2.449, Journal; ISSN: 2162-2337)

Teaching activities

2014 – 2016	Assistant lecturer, Practical exercises in information networks (laboratories, BUT)
2013 – 2016	Assistant lecturer, Network Operating systems (laboratories, BUT)
2013 – 2014	Assistant lecturer, Modern Network Technologies (laboratories, BUT)

OTHER QUALIFICATIONS AND KNOWLEDGE

Language knowledge	Czech language (native speaker) English language (level C1) German language (level A1)

Certifications

• CCNA Exploration: Network Fundamentals, Brno University of Technology, FEEC (November 2011)
• CCNA Exploration: Routing Protocols and Concepts, Brno University of Technology, FEEC (January 2012)
• CCNA Exploration: LAN Switching and Wireless, Brno University of Technology, FEEC (May 2012)
• CCNA Exploration: Accessing the WAN, Brno University of Technology, FEEC (May 2012)
• CCNP ROUTE: Implementing IP Routing, Brno University of Technology, FEEC (December 2012)
• CCNP SWITCH: Implementing IP Switching, Brno University of Technology, FEEC (June 2013)
• CCNP TSHOOT: Maintaining and Troubleshooting IP Networks, Brno University of Technology, FEEC (January 2014)
• PaloAlto Networks ACE: Accredited Configuration Engineer (ACE) Exam PAN-OS 7.0 Version (May 2017)

Awards

• 2nd Place at Student's Conference EEICT 2015. Topic: *Body-area Communications: Sci-Fi or Promising Paradigm?*
• 2nd Place at Student's Conference EEICT 2016. Topic: *In-Depth Analysis of Smart City in Modern Age*
• 1st Place at Inter-university Student Competition (MUNISS 2016). Topic: *Realization of Smart City Vision for City District Nový Lískovec*
• Master's degree with honors (June 2014)

RESEARCH PROJECTS

Project coordinator

• Agregační brána pro zabezpečený přenos dat z okamžitých měření fyzikálních veličin, (01/2016 - 12/2016)

Project participant (selected projects)

• TA186S01001 Nové metody pro optimalizaci energetické náročnosti a škálovatelnosti ultra širokopásmových lokalizačních systémů (2015 – 2017)
• NK1200746879 Zpracování studie Analýza kvality součástkové základny přijímačů HDO (2017)
• VD186S02001 Výzkum a vývoj inteligentního systému pro řízení energetických sítí a identifikaci hrozeb v energetické infrastruktuře (2016 – 2017)
• HS18457030 Studie a výběr nejvhodnější komunikační technologie pro konkrétní use case – Smart grid a provoz mřížové sítě v lokalitě Brno (2016)
• CZ.1.05/2.1.00/03.0072 Research Centre of Sensor, Information and Communication Systems (SIX), (2013 - 2016)
• HS18457025 Development of Universal Smart Gateway for Home Automation (2014 – 2015)

SELECTED PUBLICATIONS (2013 – 2017)

Selected publications in scientific journals with impact factor according to Web of Science

• HOSEK, J.; MASEK, P.; ANDREEV, S.; GALININA, O.; OMETOV, A.; KRÖPFL, F.; WIEDERMANN, W.; KOUCHERYAVY, Y. A SyMPHOnY of Integrated IoT Businesses: Closing the Gap between Availability and Adoption. IEEE Communications Magazine, 2017, vol. xx, no. x, s. 1–9. ISSN: 0163–6804. **IF: 10.435**. (Accepted for publication)

• ANDREEV, S., HOSEK, J., OLSSON, T., JOHNSSON, K., PYATTAEV, A., OMETOV, A., OLSHANNIKOVA, E., GERASIMENKO, M., MASEK, P., KOUCHERYAVY, Y., MIKKONEN, T. A Unifying Perspective on Proximity-Based Cellular-Assisted Mobile Social Networking. IEEE Communications Magazine, 2016, vol. 54, no. 5, s. 1–9. ISSN: 0163–6804. **IF: 5.125**

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• MASEK, P.; MASEK, J.; FRANTIK, P.; FUJDIAK, R.; HOSEK, J.; MLYNEK, P.; MISUREC, J.: GenTMS; Modular platform for traffic management in Smart City ecosystem. Department of Telecommunications, Brno University of Technology. 2016. (**software**).

• HOSEK, J.; MASEK, P.; KOVAC, D.; CIKA, P.; STUSEK, M.; ZEMAN, K.: OSGi Smart Hub 1. 0; OSGi-based Smart Hub Platform. Department of Telecommunications, Brno University of Technology. 2015. (**software**).

• HOSEK, J.; MASEK, P.; KOVAC, D.: SyMHPOnY 1. 0; Smart Multi-Purpose Home Gateway for Different Home Automation Services v. 1. 0. Department of Telecommunications, Brno University of Technology. 2014. (**prototype**).

• HOSEK, J.; KOVAC, D.; MASEK, P.; STUSEK, M.: Energy Dashboard 1. 0; Visualization and Management Platform for Smart Metering. Department of Telecommunications, Brno University of Technology. 2014. (**software**).

SUMMARY OF PUBLICATION ACTIVITIES

- Scientific journals with impact factor according to Web of Science: **7**
- International conferences indexed in Web of Science or Scopus: **30**
- Total number of citations according to Web of Science: **79**
- H-index according to Scopus: **5**
- H-index according to Web of Science: **3**
- Number of released products: **5**

REFERENCES

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