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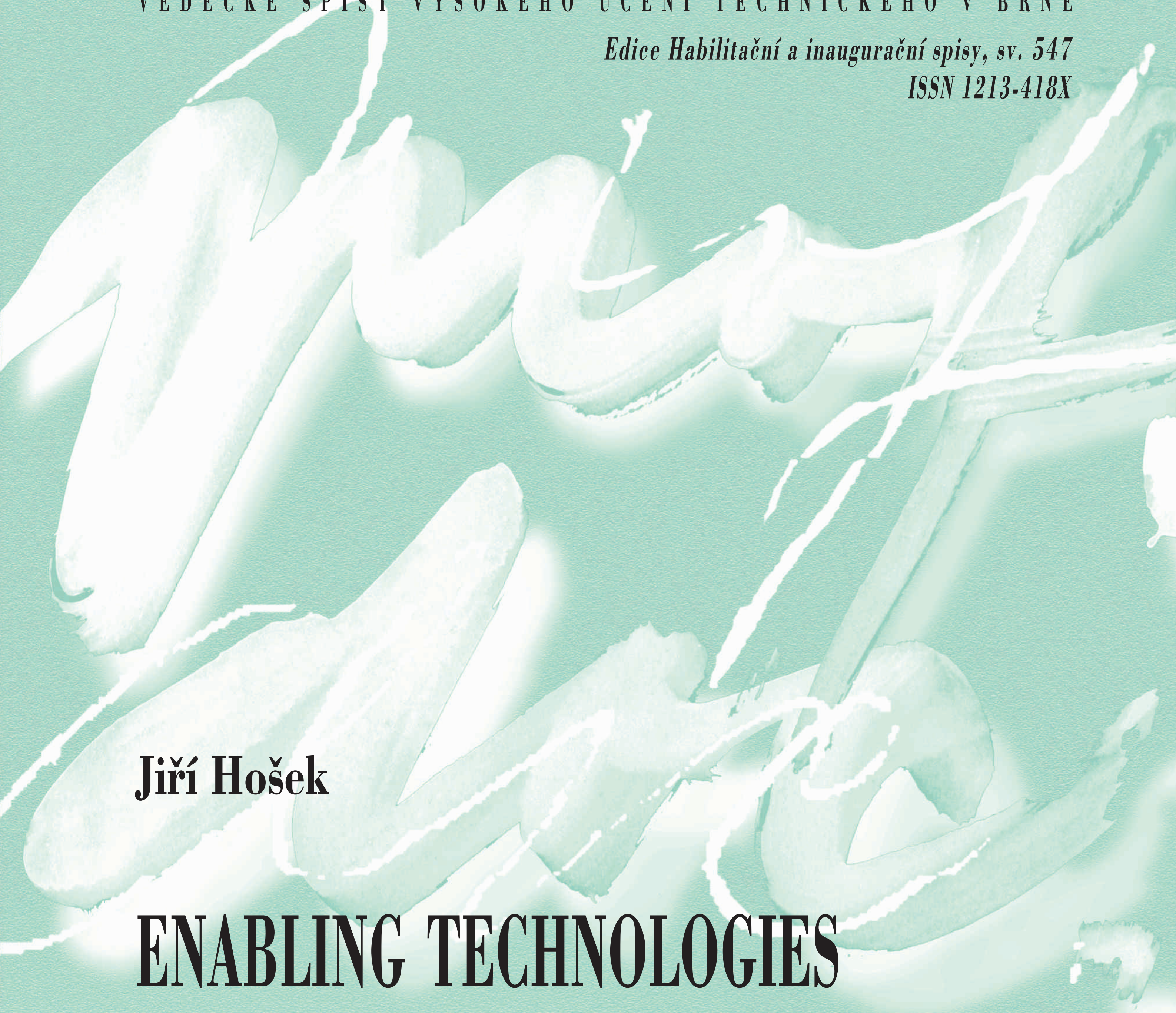

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ENABLING TECHNOLOGIES AND USER PERCEPTION WITHIN INTEGRATED 5G-IOT ECOSYSTEM

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ENABLING TECHNOLOGIES AND USER PERCEPTION WITHIN INTEGRATED 5G-IOT ECOSYSTEM

KLÍČOVÉ TECHNOLOGIE A UŽIVATELSKÁ SPOKOJENOST V RÁMCI INTEGROVANÉHO 5G-IOT EKOSYSTÉMU

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1 INTRODUCTION

1.1 Introduction and Research Motivation

When Guglielmo Marconi succeeded in performing the first radio transmission across the Atlantic Ocean in 1899, he actually opened, even that it was just about sending a single letter 'S' in the form of three dot Morse code, new era of wireless communications. After this famous breakthrough, wireless communications have been continuously transforming the way how the society is interacting towards current omnipresent connectivity as an essential part of our everyday lives [1].

It has been more than a few decades since mobile wireless communications were initiated with the first generation, analogue voice-only systems. Over the last couple of decades the world has witnessed gradual, yet steady evolution of mobile wireless communications towards second (2G, still based on circuit switching), third (3G) and fourth (4G, already all-IP) generation of wireless networks [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 (5G) will be implemented around 2020 and beyond.

Any massive real-world deployment is always preceded by thorough research stage and since we are currently around five years prior to the expected roll out of 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 reason of such extreme interest can be found 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 [3], [4]. All these aspects introduce 5G as dramatical shift, barely comparable with previous generations, based on completely new technologies and brilliant innovations which go beyond our current imagination [5].

Inspired by the above, this habilitation thesis discusses the key technologies which has been recently introduced as 5G enablers possessing highest potential [6]. As each of previous mobile generations has been driven by new applications and the associated users' demands, we assume the same also for 5G. Due to that, this work is closely evaluating different aspects of end user's perception of newly arriving technological changes and applications which is an essential performance indicator of overall adoption of 5G [7].

One of the most rapidly developing applications where the 5G is expected to fulfill its needs is Internet of Things (IoT) [8]. 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. And since it is already clear that not all these challenges can be accommodated by current wireless networks, the 5G should take this role. Following this, many already propose an inevitable integration of both worlds thus creating so called 5G-IoT ecosystem [9], [10].

It is more than evident that 5G is a very broad topic with many technical, social and as well as business aspects so it is not an intention of this thesis to cover all of them, but rather explore in more detail only few selected, *user-oriented*, domains. However, as first, the technical playground of this work, the 5G vision, is introduced by the following section.

1.2 Outlining 5G Vision

Several years ago, it was not even clear what 5G really means and what kind of technologies and applications will be the biggest drivers of this new cellular evolution. However, what was forecasted from very beginning of 5G era is the fact that this new wireless paradigm will represent a fundamental turning point how society is thinking about and utilizing the wireless communications, especially from the point of view, what (and how many) kind of devices will be interconnected and what new applications will be available.

As technical envelope of this vision, there are several broadly discussed performance criteria which are expected to be delivered by 5G. The most important of them, considered in this work, are listed below [11]:

- very **high** degree of **flexibility & intelligence** of all technology components to deliver most of the services "on-demand";
- nearly **unlimited capacity and ubiquitous coverage** introducing the "anytime & anywhere" connectivity;
- significant **increase in network capacity and throughput** (1 - 10 Gbps);
- extremely **low end-to-end latency** (below 1 ms) to enable new applications such as Tactile Internet (TI) [12], [13];
- unrestricted mobility to enhance the **mobile broadband** even **for very fast moving objects** (up to 500 km/h);
- ultra **high connection density** (up to 100-fold growth in connected devices);
- **energy efficient communication** to reduce power consumption up to 90%.

Ever increasing proliferation of smart devices, introduction of new emerging user-centric multimedia applications, together with an exponential growth of wireless data (multimedia) demands and usage, are already creating a significant burden on existing cellular networks. Therefore, 5G wireless systems, with improved data rates, capacity, latency and Quality of Service (QoS) are expected to be the panacea of most of the current cellular networks' problems [2].

Looking at the aforementioned performance criteria together with recent wireless network statistics revealing that only 36% smart devices (of the total global mobile devices) are responsible for 89% of total mobile data traffic and that 97 million wearable devices generated 15 petabytes of monthly traffic in 2015 [14], it is more than evident that new challenges are rising up. Mobile network operators, currently deploying 4G cellular systems (Long Term Evolution, LTE), are trying to handle this influx of mobile data traffic by e.g. implementing more efficient QoS-driven scheduling algorithms or increasing density of their current networks. However, whole community already understood that in order to provide sufficient Usex eXperience (UX) within such challenging environment, the fundamental changes in the design of future cellular networks are imperative [15]. As consequence, this finding opened a global research race to investigate all those challenges, find the answers to open questions and develop the winning 5G-grade technologies or applications.

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 fully uncovered. However, one cornerstone is already clear - 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 mix of directly linked communication technologies [16], [17].

While in recent cellular systems, the particular wireless technologies have been developing and operating individually, the 5G's call for a significant increase in network capacity and throughput requires a tighter inter-working between various RATs. As a result, it becomes crucial to aggregate different radio technologies as part of a common converged radio network, in a manner transparent to the end user, and develop techniques that can efficiently utilize the radio resources available across different spectral bands [18]. Consequently, the Heterogeneous Networks (HetNets) represent a key constructional block of 5G wireless networks where different RATs operating in licensed (LTE) and as well as unlicensed spectrum (Wireless Fidelity, WiFi) are jointly providing the multiplied performance [19].

As complementary to the convergence of various RATs, the mobile network operators are

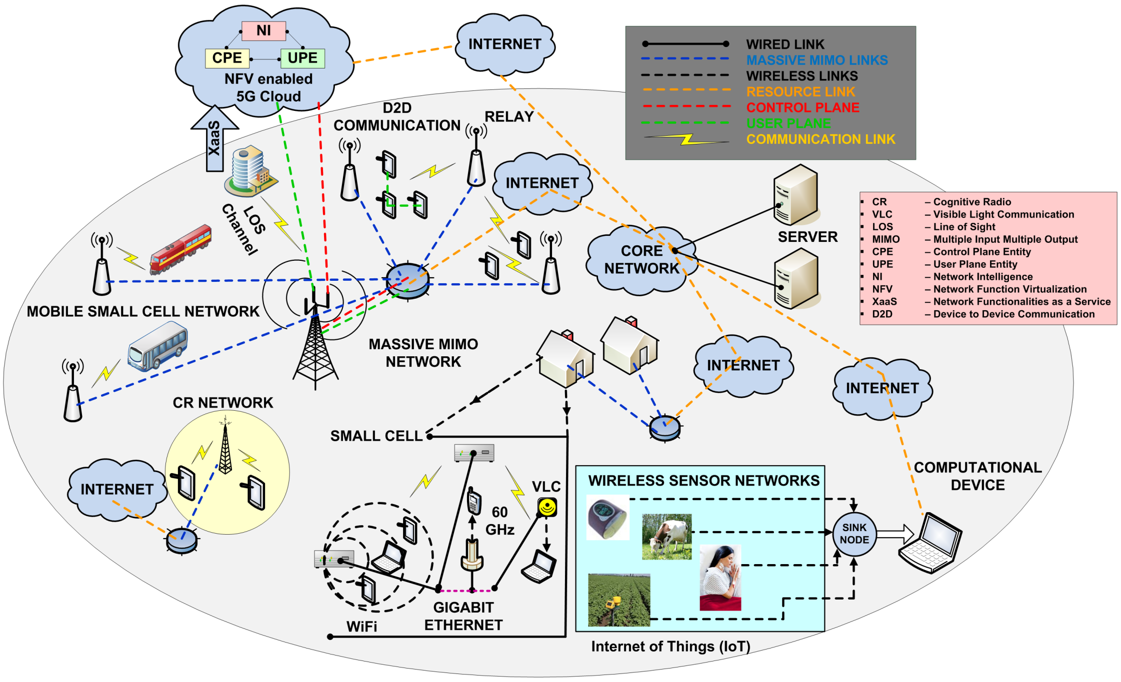


Fig. 1.1: Envisioned heterogeneous network concept of 5G

increasing the density of their networks by deploying new cells with different (rather small) coverage to boost the overall network capacity [20]. However, the multi-RAT concept together with network densification are still not giving satisfactory outputs (from 5G perspective) especially due to limited space and narrow frequency bandwidth of all legacy wireless technologies. Hence, the heterogeneous deployments have to be augmented also by novel wireless communications utilizing high frequency mmWave band ranging from 3 to 300 GHz [21]. The mmWave communications are naturally not suitable for long-distance applications since the wave can not infiltrate from dense materials efficiently and can easily be dispersed by rain drops, gases, and flora. Though, mmWave and Visible Light Communication (VLC) technologies can enhance the transmission data rate for indoor setups because they have come up with large bandwidth. This, particularly supports one of the key ideas of designing the 5G cellular architecture when the outdoor and indoor scenarios should be separated so that penetration loss through building walls can be avoided [22].

All above introduced building blocks of 5G vision are incorporated into the majority of recently introduced proposals of general 5G cellular network architecture [1], [22], [23]. The Fig. 1.1 illustrates the HetNets principle together with interconnectivity among the different emerging technologies like massive MIMO (mMIMO), Cognitive Radio (CR) network, mobile and static small-cell networks. This proposed architecture also explains the role of Network Function Virtualization (NFV) in 5G concept. The ideas of Device-to-Device (D2D) communication, small cell access points and IoT has also been taken into account by this proposed 5G model.

So, summarizing the latest research around 5G, we can see that the 5G vision is already taking more concrete shape as its technology components (further discussed in the following section) are gradually developing. In the upcoming period, we will be witnessing continuous research activities including numerous 5G live trials across academia and industry as well (some of them were introduced recently [24], [25]), which will provide an assessment of different aspects of future wireless networks and so getting these ideas closer to the end users and massive roll-out.

1.3 5G Technology Components

As mentioned above, the 5G is expected as a highly heterogeneous environment consisting of many technology components as enablers of future mobile services and applications. Following this and reviewing the most recent literature, we have selected, and introduced in this section, the key networking technologies and principles which are believed as the most significant contributors to the 5G world.

1.3.1 Extreme Network Densification

The astounding mobile traffic increase together with demand for significant multiplication of network capacity and throughput [26] call for an ultimately efficient, however, cost-effective, solution. The first option, which logically comes to mind, is adding more cells with smaller coverage, but higher throughput [27]. However, this approach is not so straightforward and easy to implement as it might look like. Moreover, there are several related challenges and also the financial return is questionable. Nevertheless, when the issues are addressed properly, the network densification will take the significant share of the surge in capacity within 5G systems [28], [29].

While operators are implementing the multi-tier architecture's idea in existing cellular systems, the base station density is increasing rapidly. Even that the HetNets were already standardized in 4G, the current architecture is not natively designed to support them. Therefore, the network densification will require some major changes in 5G where the deployment of base stations with vastly different transmit powers and coverage areas, for instance, calls for a decoupling of downlink and uplink in a way that allows the corresponding information to flow through different sets of nodes [30], [31].

The envisioned multi-tier architecture together with cell sizes shrinking will enhance the capacity and coverage via enabling dense frequency reuse per unit area and as well improving the link quality and average data rate [19]. The heterogeneity of different classes of Base Stations (BSs), e.g., macrocells, picocells or femtocells, provides flexible coverage areas. Additionally, the coverage can be improved by deploying small cells indoors (such as private houses, office buildings, public vehicles, etc.) [23].

The highly densified infrastructure augmented with multi-RAT connectivity becomes very complex system which opens several new challenges. Among them, as broadly discussed issue, an interference management (further discussed in the next section) is a matter of ongoing research. This will definitely require more advanced algorithms due to new interference situations. However, given that the inter-tier and intra-tier interferences are well managed, the adoption of multi-tier cellular network architecture is assumed to provide the expected benefits.

1.3.2 Advanced Spectrum Sharing and Interference Management

Very high heterogeneity and dense deployment of 5G wireless networks together with coverage and traffic load imbalance due to varying transmit powers of different BSs make the interference management and resource allocation problems more challenging than in conventional single-tier systems [23]. It is clear that the transmission power level of a cell affects its coverage range and the amount of interference it generates in the network. Although higher transmission power can provide wider coverage and better signal quality, it can, at the same time, cause tremendous interference to surrounding users. Moreover, also the ultra-dense deployment consisting of small cells with limited transmit power may suffer from interference issues due to the overlapping coverage. Therefore, multi-tier 5G networks urgently require an intelligent solution for the interference management. As promising candidate for mitigating interference in HetNets, the dynamic *power control* based on proper selection of the pico or femto cells' transmit power level, has been introduced [19].

Closely related to the interference management, a reasonable attention has been devoted also to the research of advanced spectrum sharing techniques which are expected to bring certain benefits as well. The efforts to develop more efficient and dynamic approaches to spectrum sharing and so increase the capacity of current mobile systems have recently resulted in a new framework known as the shared use of spectrum. The spectrum sharing indicates that a certain frequency can be used by several entities, in contrast to the traditional exclusive licensing where a frequency is allocated to a single operator or system [32].

As one of the options of efficient spectrum sharing is the Licensed Shared Access (LSA). This administrative framework allows to use more frequency bands without breaking services that are conventionally occupying these bands. The idea behind LSA is such that frequency bands are rented from their original owner (so called *incumbent*) and then used by any temporary user, referred as LSA licensee (e.g. cellular operator). A dedicated *regulator* entity keeps a database with the information on rented bands, as well as their status, and also acts as an interface between the LSA licensee and the incumbent [33]. As expected for most of 5G-grade technologies, the LSA concept will require modifications to existing cellular network management.

1.3.3 Converged Radio Networks and Direct Communications

In addition to the multi-tier aspect of HetNets, multi-RAT network components contribute extra performance enhancement as well. While previously cellular and *unlicensed* wireless technologies (e.g. Wireless Local Area Network, WLAN) were developing mostly independently, today WiFi hotspots' capabilities will become more integrated into mobile devices of the future (e.g., smartphones, tablets, wearables), and this in turn will open the door to vast number of Machine-to-Machine (M2M) services that could be offered to the cellular subscriber. As a result, it becomes crucial to aggregate different radio technologies as part of a common converged radio network, in a manner transparent to the end users, and develop techniques that can efficiently utilize the radio resources available across different spectral bands potentially using various RATs [34]. Following this approach and given that an increasing number of mobile devices are equipped with multiple radio interfaces (e.g., WiFi in addition to 4G), a network operator can also exploit the different radio networks to add low-cost capacity, and improve coverage and QoS. However, this scenario requires the operators to have a certain level of access control on the WiFi Access Point (AP) [19].

Inspired by the gains expected from HetNets, widely cited Cisco Virtual Networking Index Forecast Study [14] predicts that more than half of all traffic from mobile-connected devices (almost 3.9 exabytes) will be offloaded to the fixed network by means of WiFi devices and femtocells each month by 2020.

Peer-to-Peer (P2P) services are currently one of the main contributors to the predicted mobile data traffic growth. Since majority of P2P scenarios are involving communication between the users in close proximity, as logical implication, direct connectivity can be utilized whenever possible in order to offload traffic from the highly congested infrastructure links [35]. Consequently, D2D connections are believe to allow users in near vicinity to establish direct communication while replacing two relatively long radio hops via the BS with a single and shorter direct hop. Thus, utilizing D2D can bring about reduced power consumption and/or higher data rates, and a diminished latency in 5G networks [17].

The recent research efforts bring several studies on direct user connectivity with different levels of network involvement, however, as the most preferable application scenario, the network-assisted D2D communication is envisioned. In such case the network assistance should employ proper admission and power control on D2D nodes as well as allocate radio resources to them [36].

1.3.4 Utilization of Extremely High Frequency Spectrum

Nowadays wireless systems are operating in the relatively slim range of microwave frequencies that extends from several hundred MHz to a few GHz and corresponds to wavelengths in the range of a few centimeters up to about a meter. By now though, this spectral band, often called as "beachfront spectrum", has become nearly fully occupied, in particular at peak times and in peak markets [17]. Therefore, despite the projected efficiency of network densification and mobile data offloading, much more bandwidth is needed.

Even that the spectrum is a limited natural resource, there is an enormous amount of unoccupied spectrum at high frequencies, referred as mmWave spectrum, ranging from 3 to 300 GHz. Alternatively to the beachfront spectrum, many mmWave bands seem to be promising, including most immediately 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, offering well over an order of magnitude increase over what is available at present [15].

Another highly emerging technology operating in very high frequency spectrum is Visible Light Communication (VLC). The VLC uses off-the-shelf white Light Emitting Diodes (LEDs) used for Solid-State Lighting (SSL) as signal transmitters and off-the-shelf P-Intrinsic-N (PIN) Photo-Diodes (PDs) or Avalanche Photo-Diodes (APDs) as signal receivers. This means that the LEDs can serve dual purpose of providing illumination as well as wireless communication with very high data rates (nearly 100 Mbps in IEEE 802.15.7 standard and up to multiple Gbps in research) [37]. Thus, VLC can complement the Radio Frequency (RF) based mobile communication systems in designing high-capacity future wireless networks. The VLC idea goes actually even beyond-5G vision.

The utilization of extremely high frequency spectrum is owning broad interest of researchers as very attractive 5G enabler which, however, is opening entirely new questions and feasibility constrains. Some of the most frequently discussed issues are unfriendly channel conditions like path loss effect, absorption due to atmosphere and rain, small diffraction and penetration about obstacles and through objects respectively and signal blockage [1]. Moreover, mmWave communications have very short range by default.

Nevertheless, despite many present challenges, mobile industry including standardization bodies refer mmWave technologies as promising 5G enabler possessing high market penetration probability. To increase this potential and mitigate the aforementioned issues, different spatial processing techniques like mMIMO and adaptive beam-forming can be applied [38].

1.3.5 Massive MIMO

The Multiple-Input Multiple-Output (MIMO) systems consist of multiple antennas at both the transmitter and receiver side. By adding multiple antennas, a greater degree of freedom (in addition to time and frequency dimensions) in wireless channels can be offered to accommodate more information data [22]. MIMO technology in already implemented in many wireless systems and devices. However, obtained gains in network throughput are not sufficient enough with the respect to future 5G demands. Therefore, as a logical upgrade, mMIMO technology has been developed. The mMIMO system uses arrays of few hundred antennas which are at the same time and in one frequency slot serving many tens of user terminals [1].

The concept of mMIMO introduces several noticeable benefits highly important for future 5G networks. First of them is an enormous enhancements in spectral efficiency without the need for increased BS densification [38]. The authors in [1] even predict that due to spatial multiplexing technique utilized by mMIMO, this technology has capability that can improve the radiated energy efficiency by 100-times and, at the same time, increase the capacity of the order of 10 or more. Another expected mMIMO contributions are smoothed-out channel response or simple transmitter / receiver structure due to the quasi-orthogonal nature of the channels between each BS and the set of active users sharing the same signaling resource [39].

In order to transform current mMIMO resarch into real deployments, several challenges must first be overcome. One of the most important of them is to scale the total cost for the individual antenna element down by the same factor as the number of antenna elements is increased [39]. Furthermore, in mMIMO systems, the effects of noise and fast fading vanish and intracell interference need to be mitigated as well. As promising solutions of these issues, simple linear precoding and detection methods were introduced [22]. More mMIMO constrains are elaborated in [17].

1.3.6 Network Virtualization and Cloud-based Networking

As already discussed, to fulfill all 5G performance criteria, the wireless networks need to be much more agile, flexible and scalable. As such, two technology trends will become paramount in the future: Network Function Virtualization (NFV) and Software Defined Networking (SDN). Together, these trends represent the biggest advance in mobile communication networking in the last 20 years, bound to fundamentally change the way network services are provided [17].

The NFV will not only incorporate the core network nodes, but also the peripheral elements. As the result, the term cloud-RAN (C-RAN) is already being utilized [40]. The C-RAN (or also referred as SND RAN) is one of the assumed ways how to control different mechanisms (e.g. inter-cell interference) within such complex system as 5G network is expected to be [41].

As one of the design applications of C-RAN, the C-RAN BS concentrates the baseband signals from several hundreds of sectors/cells to a server platform for centralized signal processing. This architecture creates a super BS with distributed antennas that can support multiple protocols and dynamically allocate its signal processing resources to follow the varying traffic load within its geographical coverage [19].

Together with C-RAN architecture, NFV facilitates resource sharing among many operators. NFV enables multiple network operators to share common resources (e.g. network infrastructure, backhaul, licensed spectrum, core and RAN, energy/power, etc.). The virtualization mechanism abstracts (e.g., isolates) the physical resources to a number of virtual resources, which is shared by different consumers (e.g., service providers). The main advantages of NFV cover: high resource utilization, improved system performance, reduced Capital Expenditure (CAPEX) and Operating Expenditure (OPEX), better user experience, and easier migration to newer technologies by isolating part of the network [42].

1.3.7 Energy Efficient Communications

Similarly to other ICT domains, the design of 5G wireless networks should take into account minimizing the energy consumption in order to achieve greener wireless communication systems [43]. The green communications effort will include the design changes on both network and device side as well.

While leveraging the advances on green data centers, true C-RAN could provide an opportunity for energy efficiency, since the centralization of the baseband processing might save energy [44]. In addition, SDN principles applied in the back-end network are expected to bring reduced energy consumption as well. Moreover, by separating indoor traffic from outdoor traffic, the marcocell BS will have less pressure in allocating radio resources and can transmit with low power, resulting in a significant reduction in energy consumption [22].

On the other hand, due to constantly increasing number of *energy-hungry* multimedia applications, energy efficiency will be an important feature for 5G user experience, and hence, it is desirable that the battery-constrained wireless devices integrate energy harvesting technologies [45]. For instance, the UE can harvest energy from environmental energy sources (e.g., solar and wind energy). However, due to stochastic nature of environmental sources, the available energy levels may vary significantly over time, locations, weather conditions, etc. Therefore, harvesting energy from these sources may not be feasible for reliable and QoS-constrained wireless applications. Alternatively and probably more realistically, energy can be also harvested from ambient radio signals (e.g., RF energy harvesting) [23].

In a nutshell, the emerging field of Wireless Energy Harvesting (WEH) is based on the idea of receiving the transmitted radio signal with an antenna and converting it into a stable direct current energy source to supply the mobile device. Currently, the WEH's application domain covers IoT services, however, is expected to spread also to other 5G areas [46], [47].

1.4 Scope of the Thesis

This thesis deals with various aspects of wireless communications and services forming together the future generation of cellular networks. In particular, three key research domains, which we believe as the ones possessing the greatest potential to benefit end users the most, are comprehensively reviewed: (i) variety of emerging technologies are introduced as **5G wireless network enablers** anticipated with the capacity to cooperatively full-filed the strict performance requirements, (ii) IoT as a broad family of different services and applications with highly variable demands on communication technologies is considered as a vital component of the 5G mobile networks. In this *producer-consumer* partnership, often referred as **integrated 5G-IoT ecosystem**, the 5G is expected to offer a variety of appropriate communications mechanisms while, as a consequence, IoT will unwind its capabilities. And, finally, (iii) at the end of day, we will have to enrich and enable **high user experience** to whatever or whoever the user is and this is not a trivial task in such heterogeneous environment as 5G is envisioned. Therefore, the Quality of Experience (QoE) needs to be carefully taken into the account even from very early development stage of any network service.

As the cellular networks are rapidly developing and extending the portfolio of services offered to their subscribers, they are getting closer to the IoT world, which is, on the other hand, penetrating an increasing number of applications and so requiring more advanced communication technologies. Following the latest 5G projections, this overlap is expected to grow significantly and finally reach the level where the mobile networks and IoT will converge into the integrated *5G-IoT ecosystem*. On the top, the actual user experience and satisfaction will be always boosting or damping factor of the usability of any new technology or service and so directly influencing their cost effectiveness. Thus, all three research angles, addressed in this thesis, logically build the *technology-application-user* triangle which we anticipate as fundamental within the 5G wireless systems.

Consequently, several 5G-grade technologies and services like proximity based services, network-assisted D2D communications, design principles of Machine-Type Communication (MTC) gateway or QoE assessment methodology for online video-streaming services are discussed with greater depth as a matter of author's own research contribution. When beneficial, the fundamental research is supported by the set of advanced simulations, user campaign or experimental verification of proposed mechanisms in real-world scenarios.

2 5G WIRELESS NETWORK ENABLERS

2.1 General Background

In this section, we continue in the direction of Section 1.3 while discussing selected wireless technologies that are believed by many as the most promising to enable the vision of 5G wireless networks and fulfill especially the performance requirements identified earlier. The purpose of developing all these technologies is to enable a dramatic capacity increase requested by 5G with efficient utilization of all possible resources. Based on the well-known Shannon theory, the total system capacity C_{sum} can be approximately expressed by [22]

$$C_{sum} = \sum_{HetNets} \sum_{Channels} B_i log_2(1 + \frac{P_i}{N_p}), \tag{2.1}$$

where B_i is the bandwidth of the *i-th* channel, P_i is the signal power of the *i-th* channel, and N_p denotes the noise power. Following the Eq. 2.1, it is clear that the total system capacity C_{sum} is equivalent to the sum capacity of all subchannels and heterogeneous networks. Therefore, as already introduced in the sections 1.2 and 1.3, in order to increase C_{sum}, we can increase the network coverage (via heterogeneous networks with macrocells, microcells, small cells, femtocells, relays, etc.), number of subchannels (via mMIMO, spatial modulation, interference management, etc.), bandwidth (via cognitive radio networks, mmWave communications, etc.), and power (via energy-efficient or green communications' principles).

Due to increasing complexity in network management and coordination among multiple network tiers, the network elements will have the capability of self-organization (e.g., autonomous load balancing, interference minimization, spectrum allocation, power adaptation, etc.) [48]. However, the 5G will require radical changes not only in the design of network components, but also the User Equipment (UE) needs to be featured by more advanced algorithms to accommodate and efficiently takes the advantage of all 5G-grade technologies. To reach the required performance limits and fully exploit the HetNets environment, we can expect that UE will have simultaneously several active connections to more than one BS or AP using the same or different RATs operating in multiple spectrum bands. Nevertheless, the backward compatibility (e.g., with existing technologies such as 3G and 4G) should be preserved, because we can not expect any sudden transition towards new generation of cellular systems.

To this end, all the discussed 5G technologies provide a promising future in terms of significant improvements of wireless networks capacity and coverage and so fulfill the performance desires. However, a lot of research work and experimental evaluations need to be done in near future to find sufficient solutions to most of current issues and so increase the user adoption level of 5G vision.

2.2 Author's Focus and Contribution

Earlier in this work, the key 5G enablers and related challenges have been introduced. It is clear that the anticipated 5G vision brings large number of issues which attract research community significantly. Motivating by this, author and his colleagues have been thoroughly investigating three 5G-grade technology domains which they consider as highly important to unfold the 5G ideas. The main contribution and results created over last three years are provided by the following text as a summary of five most important author's publications [49], [50], [51], [52] and [53].

2.2.1 Transmission Power Control in Cellular Access Networks

As discussed earlier, the effective BS's transmission power control is crucial requirement to mitigate the inter-cell interference within the HetNets deployment. Inspired by this, we have been concentrating on the problem of efficient RAN modelling and estimation of the throughput available for the clients in LTE networks with particular focus on indoor environment [49].

To provide the required bandwidth to the users the operators are deploying heterogeneous networks, with LTE BSs covering very small areas in locations with high bandwidth demand. The deployment of indoor cells needs to be coordinated with the configuration of the remaining part of the network, to minimize the inter-cell interference. The LTE is designed for frequency reuse 1, which means that all the neighbour cells are using same frequency channels and therefore there is no cell-planning to deal with the interference issues. Therefore, the transmission power of the cells needs to be adjusted appropriately, to limit the area where signal overlaps and so minimize the interference.

To estimate the inter-cell interference and other network parameters like throughput or radio signal level of the indoor cellular system, we have developed an analytical model of the building, where each wall was mapped as an obstacle [49]. The model was based on the Free Space propagation model, but the attenuation caused by walls was added. We assumed that internal small walls have attenuation 7 dB, external walls (and big internal walls) have attenuation equal 15 dB, as no detailed measurements were available.

In order to increase the accuracy of our analytical model and supply it by practical inputs, we have proposed a methodology for experimental measurements of the key characteristics like Signal to Interference plus Noise Ratio (SINR), Received Signal Strength Indicator (RSSI), network throughput and latency between the UE and remote test server for both uplink and downlink directions. Following this, we have realized a series of measurements in live 3rd Generation Partnership Project (3GPP) LTE-A network. In Fig. 2.1, the comparison of the estimated network throughput is presented and compared to the measured values [49]. We can observe that the model has good match for the locations with very high signal level, but introduces a large error for the points further away from the BS. The explanation of this drawback is the fact that the model does not include the reflections of the radio signal from the walls, what decreased the signal level and estimated throughput in locations further away from the BS. Improvement of this issue together with further model's upgrade is planned as our future work within this domain.

2.2.2 Performance Evaluation of Mobile Data Offloading

One of the aforementioned techniques how to handle the enormous amount of cellular traffic is mobile data offloading where the alternative network infrastructures / technologies are utilized to support delivery of the data traffic originally intended for cellular networks. Techniques of mobile data offloading help to provide an optimal usage of available radio resources and load-balancing among the available radio resources.

In [50], we are addressing the question how to overcome the RAN congestion by offloading a part of the data traffic to complementary access networks e.g. by using WiFi infrastructure whenever needed and identified as beneficial. Our offloading strategy is utilizing unlicensed IEEE 802.11 links as the most natural and broadly supported choice for an alternative radio technology to increase the HetNet's performance.

In our approach, we assume the baseline scenario where all traffic is primarily transferred via LTE network and IEEE 802.11 link is utilized as a supportive element tasked in case of high occupation ratio of LTE. In order to analyze this concept and due to our extensive experience with Network Simulator 3 (NS-3) tool, we have implemented the Access Network Discovery and Selection Function (ANDSF) offloading algorithm into NS-3 and consequently performed a

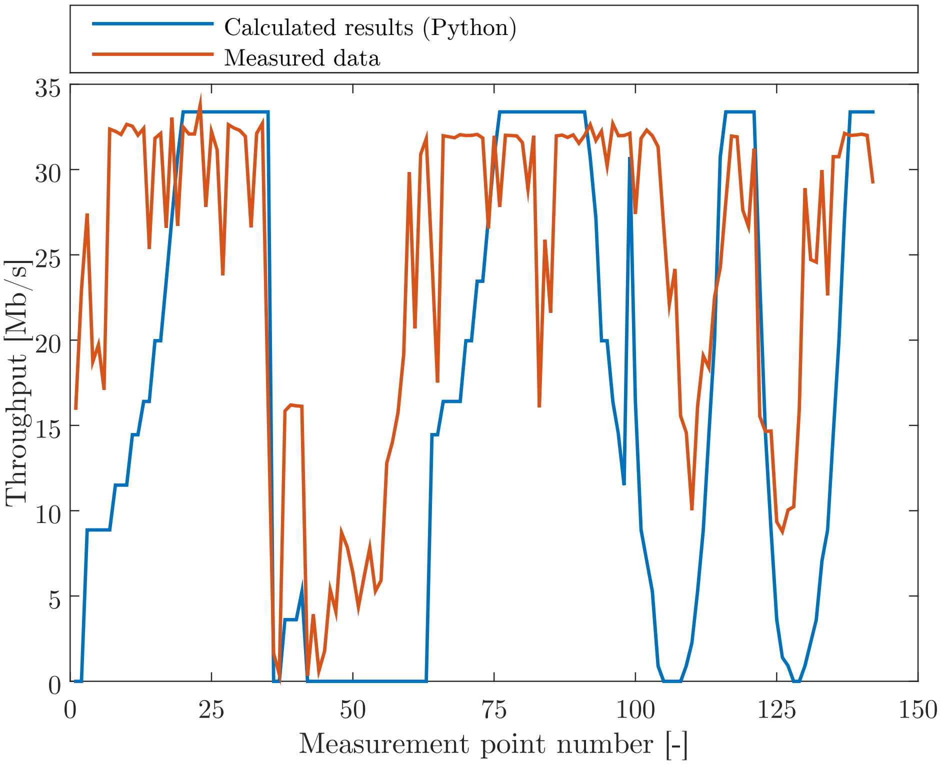


Fig. 2.1: Comparison of throughput values calculated by analytical model and measured in real LTE network

set of simulations to evaluate different mobile offloading-decision techniques. As the threshold, we have compared the SNR (Signal-to-Noise Ratio) and throughput. The topology of mobile data offloading scenario implemented in NS-3 is shown in Fig. 2.2.

Through our simulation-based evaluations have demonstrated the data offloading from licensed LTE network onto unlicensed WiFi links as efficient approach to reduce the load of the cellular infrastructure and improve the user performance. Our results [50] show better performance (higher average BR) for the scenario when the offloading was initiated by the throughput threshold. This finding supports also the use case when the SNR level is high (user is close to BS / AP), however a user experience is low due to high network congestion.

2.2.3 Network-assisted Direct Communication between Users in Proximity

D2D communication technology as part of 3GPP LTE Release 12 specification [54] enables novel unprecedented opportunities for next-generation P2P and location-based applications and services [51]. Most of these new opportunities emerge from discovering and exploiting user proximity, which is provided by virtue of location services in contemporary mobile broadband networks. Together with improvements in network capacity, latency, as well as individual user throughput and energy efficiency, D2D also brings along attractive new business cases for network and service providers.

However, introducing D2D technology within today's network infrastructure poses a number of challenges and requires updates to the longstanding cellular architecture. Therefore, to conduct a comprehensive feasibility study and reveal the practical promises of D2D communications, we have carefully designed a trial development and deployment program. Our LTE-assisted D2D trial was aimed at demonstrating how the direct connectivity paradigm

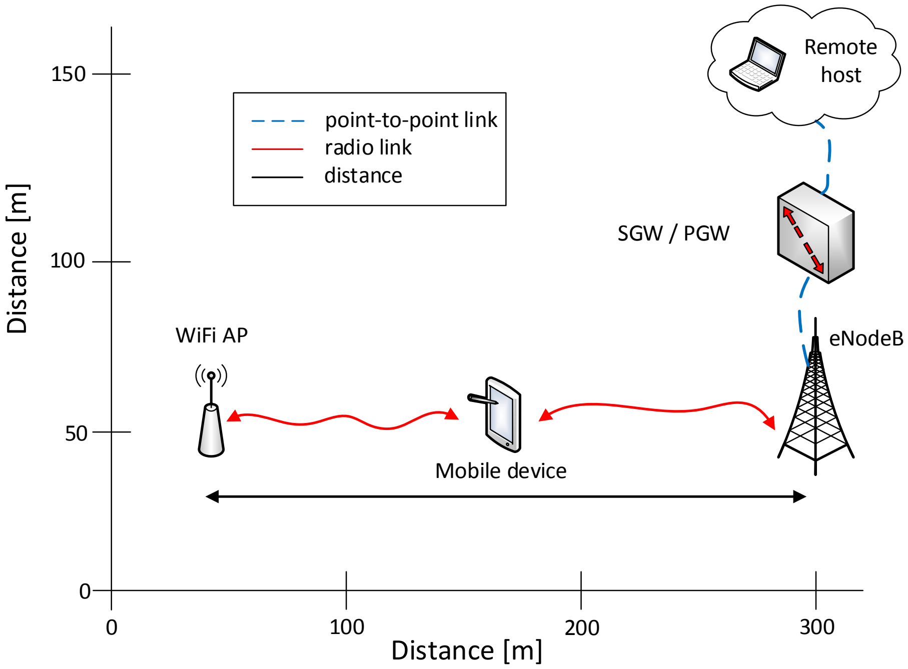


Fig. 2.2: Topology of implemented mobile data offloading scenario

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 [51].

As a basis for our trial, we have utilized the experimental LTE network of Brno University of Technology (BUT), Czech Republic, which supports most of the functionality expected of LTE Release 10 communications systems (see Fig. 2.3). During the trial, we upgraded the LTE network of BUT with our own implementation of Proximity Services (ProSe) functionality as envisioned by the 3GPP specifications.

Presently, the most widely adopted technology candidates for direct connectivity are Bluetooth and WiFi, which operate in the 2.4 GHz unlicensed spectrum. Other popular wireless networks, such as those proposed by IrDA and ZigBee alliances, are not targeted for generic D2D communications by their design. As a result, Bluetooth is mostly used today for personal area networking, whereas WiFi remains popular whenever high-rate user device connectivity is required. However, employing conventional WiFi and Bluetooth for D2D communications is rather cumbersome and does not guarantee any QoS levels. Addressing the usability problems to some extent, a WiFi-Direct (WFD) protocol has recently been introduced. WFD, which is natively supported by most of handheld devices, enables direct communication possibilities without the need for WiFi infrastructure, and does so transparently with minimal user interaction; thus, this essentially allows a device to act as a network controller. WFD also provides a way to set up multiple networks at the same time, thus enabling multiple devices to communicate IP data directly between each other [51].

For the network-assisted D2D to operate efficiently, a management entity (so called D2D server) needs regular updates on the current locations of users. In LTE, such information is conventionally aggregated by the evolved Serving Mobile Location Centre e-SMLC (e-SMLC) entity to be then made available for the user devices via Secure User Plane Location (SUPL) bearers [51].

In the considered proximal scenario, the D2D server accesses the location information on behalf of the UE, and then has to draw conclusions on whether other UEs are sufficiently close

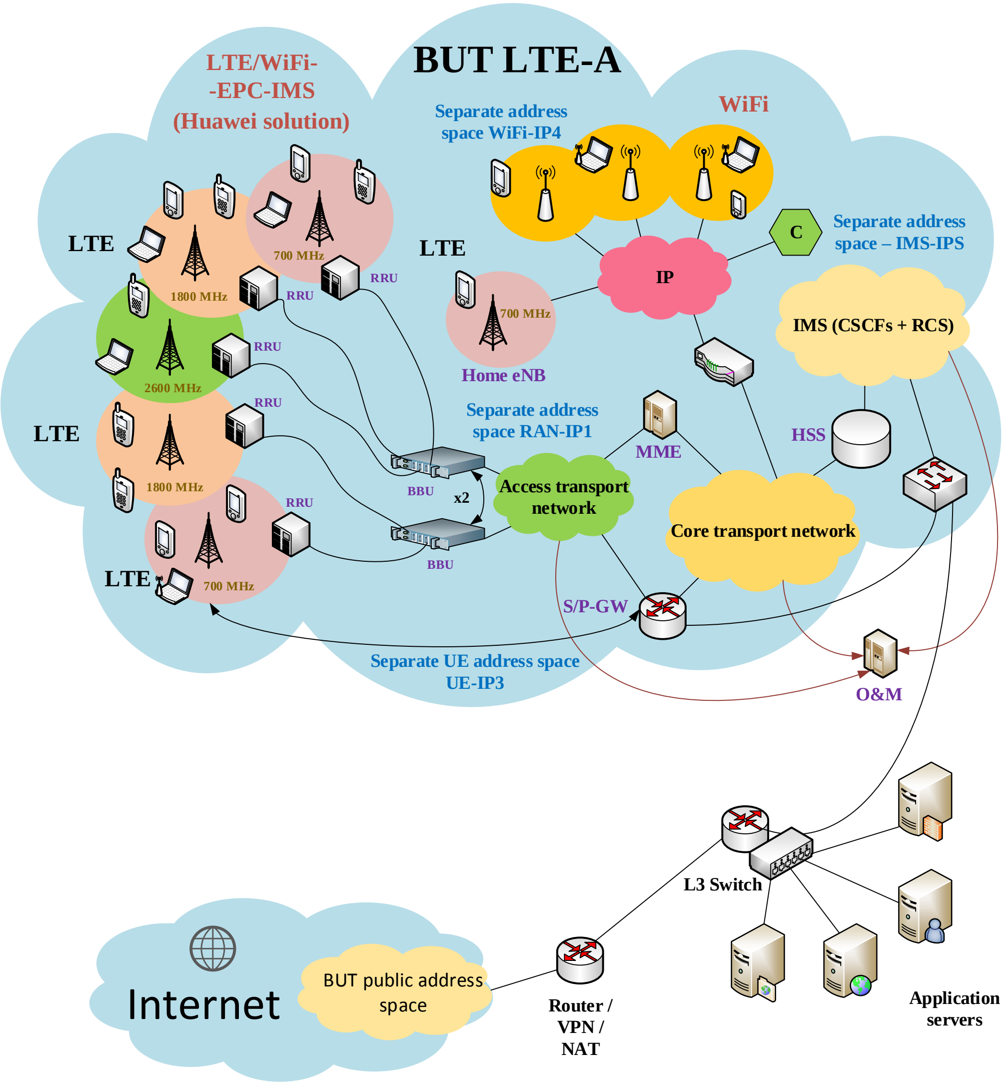


Fig. 2.3: Topology of experimental LTE-A network at BUT

to each other to initiate direct communication. An example of such decision logic is presented in Fig. 2.4. 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.

To this end, proximal interaction requires that a network dynamically adapts its topology to reflect the current application-layer requirements in a manner not impeding the everyday social routines of human users. Our proposed D2D communication framework, detailed in [52], appears to be the first attempt to address this issue.

While the technology behind network-assisted D2D communication is already taking shape as the respective standardization and implementation efforts gain momentum, the entire user perspective on this new type of environment is nowhere near well understood. To overcame this issue, future research on D2D communication should concentrate on constructing incentive-aware applications and services, and may incorporate the following major steps [52]:

- Proposing feasible D2D-aware scenarios
- Developing D2D-centric system architectures
- Designing efficient D2D operation mechanisms
- Conducting performance evaluation of prospective D2D solutions
- Leveraging available D2D benefits for operators and for clients

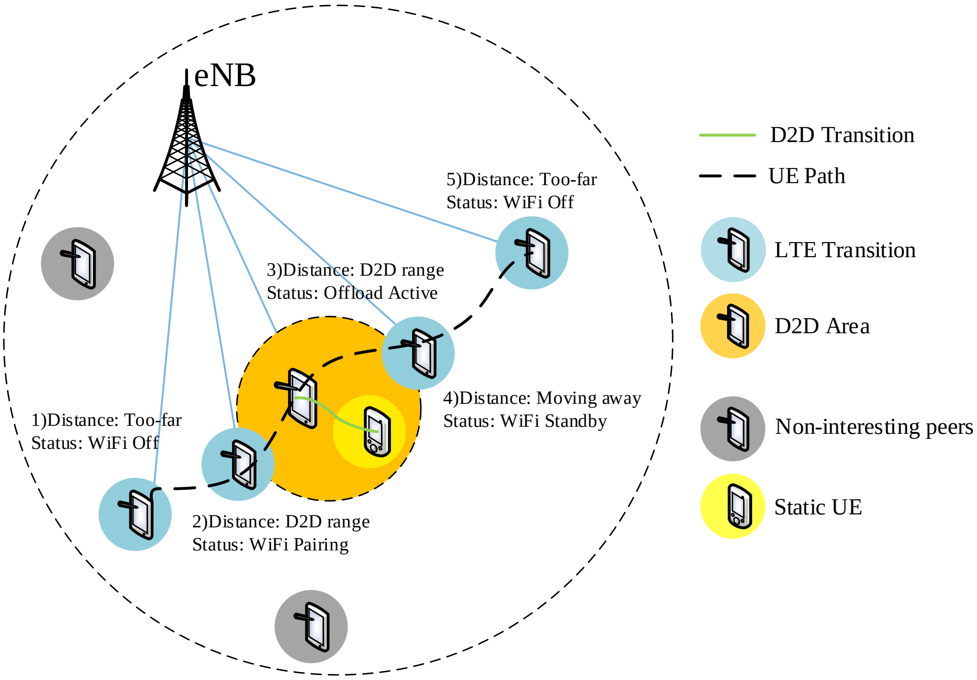


Fig. 2.4: Switching logic between LTE and proximal D2D connections

In light of the above, a major hurdle to ultimate user adoption remains the question of how D2D service providers can earn their customers' trust and deliver security, privacy, and reliability when accessing, processing, and transferring sensitive user data. Presently, the crucial aspects of security, privacy, and trust in the context of assisted D2D communication have not been sufficiently explored. Hence, they constitute an emerging research area riddled with numerous challenges connected with how a human user would utilize, and feel about utilizing, this new technology. We believe that the cornerstone security-related problems in the context of assisted D2D (with a central entity facilitating system operation) might be drastically different from similar problems in both conventional client-server and P2P architectures. Indeed, enabling D2D communication is an attractive way of alleviating potential vulnerability of centralized systems with a single point of failure.

In order to provide the desired reliability, future D2D communication systems would require new efficient means to handle intermittent connections. In real-world situations, the hierarchical security framework would need to operate without access to the application server due to the unreliable nature of wireless links. Due to the larger scale of today's networks, disruptive overloads can easily occur naturally, or could be caused by a cyber-attack, but in neither case, they should not impact the connectivity and user experience.

Our extensive research on assisted proximity-based mobile communication reported systematically throughout this work confirms that the enabling wireless technology is already mature enough to accommodate spontaneously and opportunistically connected users. With our proposed prototype implementation, current 3GPP LTE networks may supply multi-radio 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. Moreover, the broad research knowledge of human behavior and social interactions could also be utilized to further improve on any significant limitations of present technology, preferably at the early stages of platform design and connectivity optimization.

3 EMERGING IOT PARADIGM

3.1 General Background

The idea of IoT as a communication network of smart devices was firstly mentioned in [55], where the applications for automated inventory systems, introduced in 1983, were described. However, the concept of IoT has become part of a shared vision of future Internet in 1999 [56]. Today, the IoT transforms to well-known communication paradigm that envisions in the past unimaginable, today discussed and in near future fully deployed IoT vision, in which the objects of everyday life will be equipped with micro-controllers (System on Chip, SoC), transceivers for the digital communication, and suitable protocols what will enable communication between various number of objects and users.

Furthermore, by enabling easy access and interaction with a wide variety of devices such as, for instance home appliances, surveillance cameras, monitoring sensors, wearables, vehicles, and so on, the IoT will advance the development of a number of applications that make use of the enormous amount of M2M data by such objects to provide new services to citizens, business sector (companies), and public administrations. Indeed, this paradigm finds applications for IoT in many different fields and mass markets where such connectivity was not expected before (e.g., industrial automation, medical aids, emergency services, mobile healthcare, elderly assistance, intelligent energy management and smart grids, traffic management, etc.), see Fig. 3.1 [57], [58].

However, such a heterogeneous domain of applications makes the identification of technological solutions capable of satisfying the requirements of all possible application use cases a formidable challenge. This difficulty has lead to the proliferation of different and, in some cases, incompatible proposals for the practical realization of IoT systems – a large variety of communication technologies has gradually emerged, trying to reflect a large diversity of application domains and especially communication requirements [59], [60]. Some of these communication technologies are prevalent in a specific application domain (with respect to the specific use case), such as Bluetooth Low Energy (BLE) in Personal Area Networks (PANs) [61], and ZigBee in Home Automation Networks (HANs) [62]. Other technologies, such as WiFi (IEEE 802.11 family), Low Power Wide Area (LPWA) networks [63], and cellular communications (e.g., Machine-type Communication (MTC) using 3GPP “4G (LTE) machine-type communication”) have a broader communication scope. In addition, the possible landscape for IoT is constantly and rapidly evolving, with the new proposed technologies, and with the existing ones going into new application domains.

Today, the key distinction is appearing between *consumer IoT* (cIoT) and *industry IoT* (iIoT), with clear implication on used technologies and business models [59]. The cIoT aims at improving the quality of everyday life for people by saving time and costs (money). It engages the interconnection between consumer (electronic) devices, as well as almost any devices belonging to the user environments such as smart homes, offices, and smart vehicles – belonging to the paradigm named “smart cities”.

On the contrary, iIoT focuses on the integration between Operational Technology (OT) and Information Technology (IT) – how smart devices (machines), networked sensors, and data analytics (big data paradigm) can improve Business-to-Business (B2B) services across the wide variety of market sectors and activities. It generally implies M2M communication, either for application monitoring (e.g., traffic monitoring) or as a part of self organized systems without human intervention (i.e., autonomic industrial buildings) [60].

As can be seen, despite their evident differences, these two domains of IoT share general communication requirements (e.g., scalability, suitable protocol stack implementation in constrained (embedded) devices, support of IP connectivity). Nevertheless, the specific communication requirements given by iIoT and cIoT can differentiate in terms of reliability, QoS and privacy [10]. In case of the cIoT, we are typically speaking about the machine-to-user

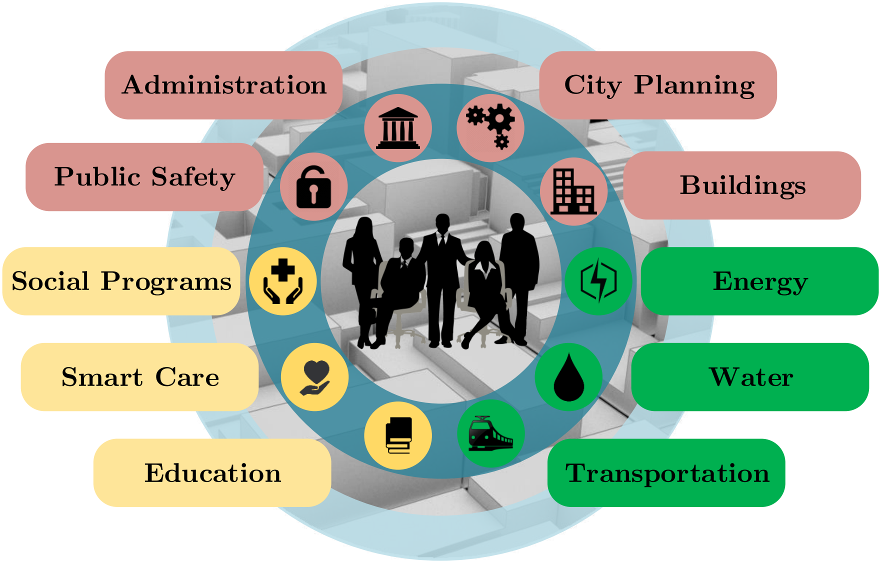


Fig. 3.1: Application use-cases for IoT domain

communication in the form of client-server interactions. Desirable features of cIoT are low power consumption, simple installation, integration, interoperability and maintenance [64]. Indeed, the cIoT paradigm is currently unfolding with the arrival of fitness and health tracking systems, smart watches and smart devices equipped with wide variety of sensors (e.g, smartphones, tablets, etc.) and requires a power efficiency, in order to enable long term monitoring using small (portable) embedded devices, as a part of "smart" environment in our everyday life (often named as a smart city paradigm). At the same time, mentioned applications should have a minimal risk of exposing such sensitive (private) data as health status or life habits. Following the exponential increase of the number of smart nodes and of exchanged information, the potential vulnerabilities to the system to attacks and to privacy leaks are multiplied [65].

Opposite to the cIoT, iIoT evolves from wide variety of systems employing the M2M communication for control processes and monitoring [10]. In such use cases, iIoT is the output of the integration (using the Internet) of hardwired and often disconnected solutions, usually based on proprietary communication protocols and architectures. Such integration process enhances the potential of isolated industrial factories by amplifying their flexibility and manageability, and disclosing the opportunity to deploy new services [60].

Large group of the iIoT, together with some of the cIoT communications, have to satisfy demanding requirements in terms of timeliness and reliability [58]. Frequently, the information exchanged is crucial for ensuring a correct and safe behavior – processing tasks under the control. Following that fact, the communication network has to be designed in order to (i) meet binding delay requirements, (ii) be robust to data losses, (iii) be safe and resilient to damages (energy / communication blackouts), and target to desired balance between CAPEX / OPEX and system availability. Cellular technologies and especially currently deployed 3GPP LTE networks [65], are the most engaging communication technologies in the modern IoT connectivity landscape – offering wide coverage, (relatively) low deployment costs, high security level, access to dedicated (licensed) spectrum, and simplicity of management [10]. However, these cellular networks were designed for optimized broadband communication networks – they do not support the proper way (idea) of the MTC communications.

Thus, the arrival of the 5G networks represents a potentially disruptive element in such a context. The increased data rate, reduced end-to-end latency, and improved coverage for MTC communication with respect to current 4G (LTE) offer the potential to cater for even the most demanding IoT applications (use cases). Indeed, in terms of M2M communication requirements, it supports the large amounts of (embedded) devices and enables the vision of a truly connected world (Internet of Everything, IoE). In addition, 5G is expected to play the role of a unified enabler (interconnection framework), facilitating a seamless connectivity of wide variety of sensors within the Internet. Following this together with assumptions that 5G will bring essential changes in design of wireless networks' architecture and so support IoT requirements by default, the "5G-IoT ecosystem" term has been introduced recently as the result of these integration efforts. Inspired by this, the thorough research of converged 5G-IoT ecosystem is a principal target of this thesis.

3.2 Author's Focus and Contribution

This section provides insights into author's research connected mostly with the cIoT. Particularly, the methodical design of HAN gateway, modelling and practical evaluation of Wireless M-Bus (WM-Bus) technology or emerging M2M communications are addressed. The described research is mainly based on six selected author's publications [66], [67], [68], [69], [70], and [71] as the ones providing most comprehensive picture of author's research in IoT domain.

3.2.1 Key Design Principles of Home Automation Gateway

The Internet of Things creates the means for interconnection of highly heterogeneous entities and networks bringing a variety of communication patterns, including Human-to-Human (H2H), Human-to-Machine (H2M), and M2M communications. IoT in general and wearable technology in particular empower the industry to develop new technology in almost unlimited numbers [14], [70]. It becomes obvious that to manage devices and services in IoT, more than one communication protocol has to be deployed. On the other hand, it is not always necessary to develop entirely new platforms to satisfy the demands of IoT services, but also already existing protocols should be taken into account as possible candidates for certain IoT use cases. For example, if we take a closer look at the architecture of 4G networks we can see that the IP Multimedia Subsystem (IMS) is a mandatory part of LTE architecture providing the possibility of using Session Initiation Protocol (SIP) for transmitting M2M data. Inspired by that and following our extensive research in this field, we have decided to convert the IoT vision for smart homes and designed from scratch the Machine-type Communication Gateway (MTCG) shipped with the universal software layer (framework) covering the principles of cIoT, see Fig. 3.3 [70].

Together with our industrial partners we have been working on the design of MTCG to meet current requirements with respect to supported protocols (application / transport layers) and widespread communication technologies used by various type of sensors (embedded devices) [66], [69]. Our designed platform, called *Smart Multi-Purpose Home Gateway* (SyMPHOnY) [72], is based on the aforementioned requirements given by the cIoT and iIoT as well. The created platform implements support for the state-of-the-art technologies [66], [70] fulfilling very strict requirements of the current IoT domain. Providing the insight into the whole development process (all materials and source codes are available for download on GitHub [72]) we believe that our created solution can fit into the planned 5G ecosystem, especially in today's world, where IoT brings new challenges which cannot be solved solely by a single technology, but rather by the harmonized set of communication platforms, protocols and applications which all create the 5G vision [10]. The emerging 5G-IoT ecosystem will act as a bridge between a massive number of energy- and power-constrained smart objects deployed e.g., within a connected home and remote cloud-based applications (see Fig. 3.2). While there is an undivided attention given by industry and academia to the 5G communication technologies, the deployment of home automation scenarios is somewhat lagging behind. Therefore, we target to bridge this gap by investigating the promising communication candidates for connected home.

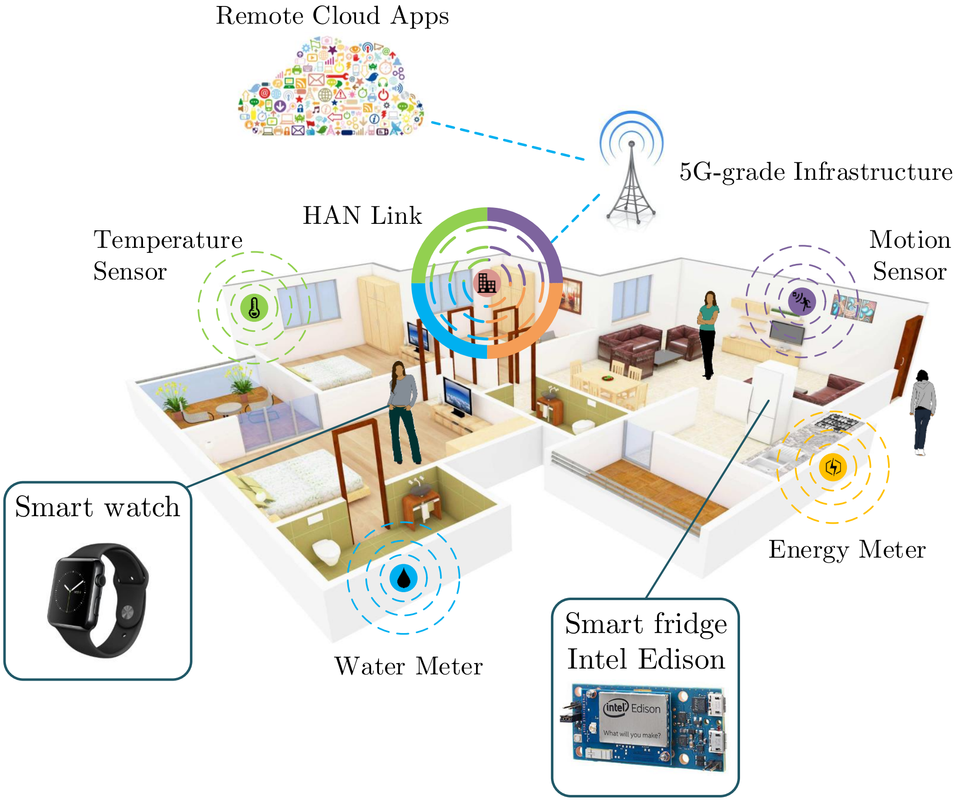


Fig. 3.2: In-house deployment of smart meters / sensors and its integration within 5G infrastructure

This leads us to the question of the choice of the suitable communication technology / standard providing the energy efficiency, short message format and support from the industry companies. Following our previous works within this field [66], [67], [68], we selected the WM-BUS [69] as a promising driver for communication between devices (direct communication (Machine-type Communication Devices MTCD - MTCD) and communication from smart device to the aggregating node (MTCD - MTCG)). The topology of WM-BUS network can differ depending on the level of automation required for the application. Usually, in static configuration, a WM-BUS network can consist of three types of nodes: meters (transmission mode T or S), repeaters (mode R) and concentrators (mode C). Meters periodically send broadcast messages containing the current information about the measured values [69].

While considering SIP as a perspective IoT communication protocol, we aimed in SyMPHOnY at developing an appropriate data structure inside the SIP message. Nowadays, JSON format acts as one of the most acknowledged drivers in case of IoT / M2M data structure. On the other hand, there are new emerging projects trying to rethink the aspect of M2M data sharing. One of them is Protocol Buffers which stands for the Google's language-neutral, platform-neutral, extensible mechanism for serializing structured data. Based on that, we have realized the live trial [72] where both structures were practically implemented and tested.

As an output of testing of proposed schemes (JSON and Protocols Buffers) in real use case (using the IMS infrastructure of Telekom Austria Group and real sensors / meters) [70], we can conclude that both proposed structures (often named as a schemes) together with SIP as a container for data transmission represent the fully functional approach to transporting M2M data over future Internet. Furthermore, the created solutions are ready for further modifications (adding new meters or updating current meter parameters).

Using the potential of the received M2M data, today known as the "big data" paradigm, we have realized together with our industrial partners new use case aiming at the data analysis

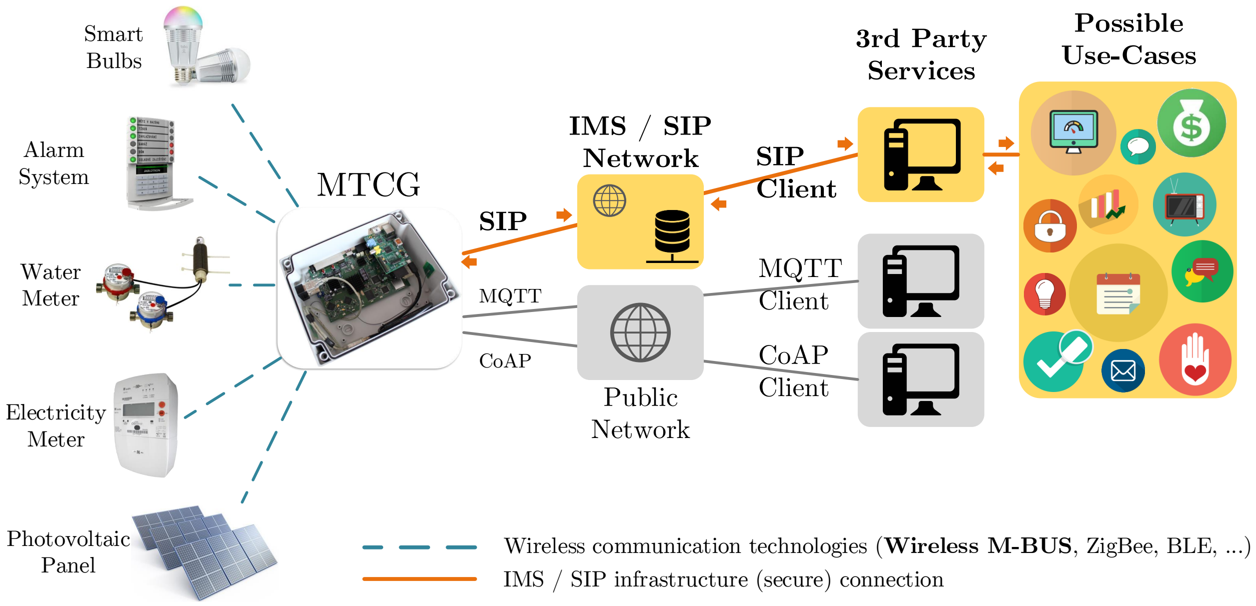


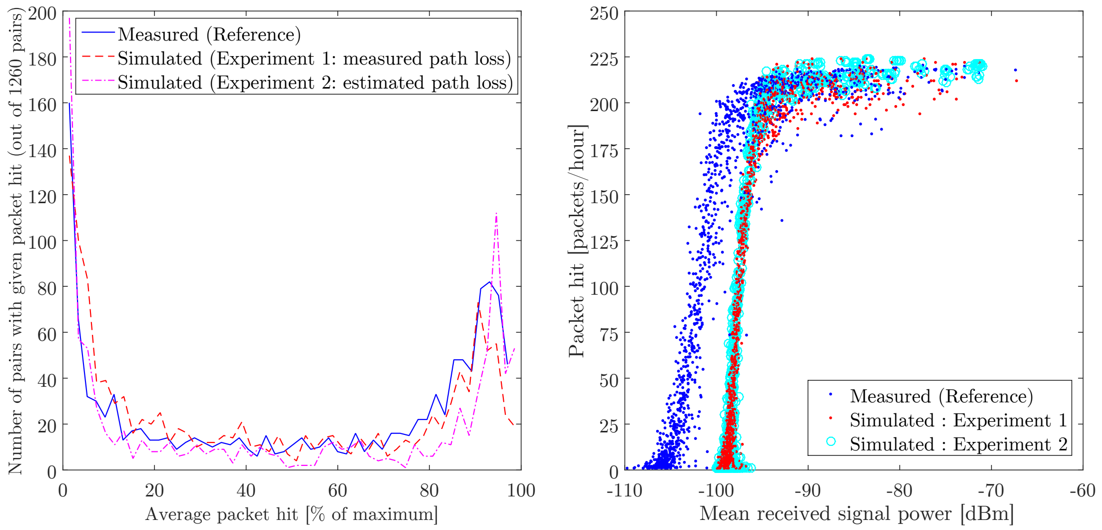
Fig. 3.3: MTCG is able to aggregate information from arbitrary smart devices and automate actions based on user-defined or network-defined policies using telecommunication operators' technologies

and visualization. Received data at the side of MTCG is sent to remote servers maintained by the energy provider(s) in the created data scheme as a SIP message. In order to convince users to be more *energy-consumption aware*, it is really important to provide them (not only to utility providers/distributors) with measurement data in real-time and attractive form. There many user friendly solutions to visualize data, e.g., Digital Living Network Alliance (DLNA), smart TV, Universal Plug and Play (UPnP) media frameworks, or social networks (e.g., Google+, Facebook, Twitter, etc.), but usually, the bindings (interconnection) between smart devices (individual sensors (MTCD) or the home gateway MTCG) and the visualizing application are missing. Therefore, our developed solution is addressing this specific issue [66].

3.2.2 Communication Technologies in 5G-IoT Applications

To unfold the IoT applications in long-term perspective, we need new, faster and more secure forms of data exchange in comparison with the solutions in the current networks. In particular, the emerging ecosystem of things (sensors) surrounding us will fuel the 5G concept within a few years [10].

Evaluating the fastest developing IoT applications, we addressed also the scenario of smart grids, where the key information about the electricity / water consumption is collected by the aggregation node [66], [70]. Since the selection of the most sufficient communication technology is critical step of any deployment, we provide a tool to assess the behavior of WM-BUS devices and so plan properly their practical roll-out in dense urban areas with respect to the key metrics such as interference between installed devices, energy efficiency (battery life), active / idle time, transmission range and probability of successful data delivery. All these requirements were taken into account during the implementation of WM-BUS into our simulation environment based on NS-3. We have paid specific attention to the utilization of the latest version of WM-BUS standard (following the requirements given in EN 13757-4:2005) and therefore our created module is able to deliver results where the data message follows the structure used in today's smart devices. As a verification of the obtained data from our module, we used the



(a) Number of concentrator-meter pairs being in a given hit rate range.

(b) Data hit vs. path loss from all measurements.

Fig. 3.4: Wireless M-Bus model calibration

data set provided by Kamstrup - one of the leading European companies in the smart grid communication domain [69].

Our constructed simulation module developed in NS-3 tool is open source and available for download on GitHub [69]. We believe that it might be considered as a powerful tool to estimate the ratio of successfully received data in case of using WM-BUS communication protocol between meters and concentrator(s). To achieve this functionality, the calibration data provided by the Kamstrup company served as a test data set. As a consequence, the proposed module is able to predict the general trend of hit rate (successfully received data from meter on the concentrator side) in the real deployment, see Fig. 3.4(a) and Fig. 3.4(b). Based on these results the created module provides an excellent correlation in range -100 dBm to -70 dBm. On the other hand, the discrepancy at the lower values can be seen. This behavior is caused by the frame dropping algorithm; the logic will be modified as our future work to better recognize the signals in the dubious range.

3.2.3 Evaluation of Cryptographic Primitives for IoT Devices

As it is common for new and highly innovative digital technologies, the wearables, as emerging IoT market, will also challenge existing social and legal norms. In particular, wearable technologies raise a variety of privacy and security concerns, which should be addressed immediately. Without strong security frameworks capable of being executed directly on wearable devices, attacks and malfunctions might overshadow any of the expected benefits.

We expand our vision of security in IoT domain not only on classical cryptography but also on pairing-based algorithms by evaluating their usability for wearables and other constrained IoT devices (smart watches, smart phones, and embedded devices) [71].

In particular, pairing-based cryptography is often used in modern solutions to implement privacy-enhancing features that are difficult to achieve with conventional asymmetric cryptography. Using bilinear pairing operations, it is possible to design schemes like group signatures anonymous attribute -based credentials or identity-based encryption [71]. Some of those mechanisms are particularly important for the IoT system operation, such as efficient revocation of

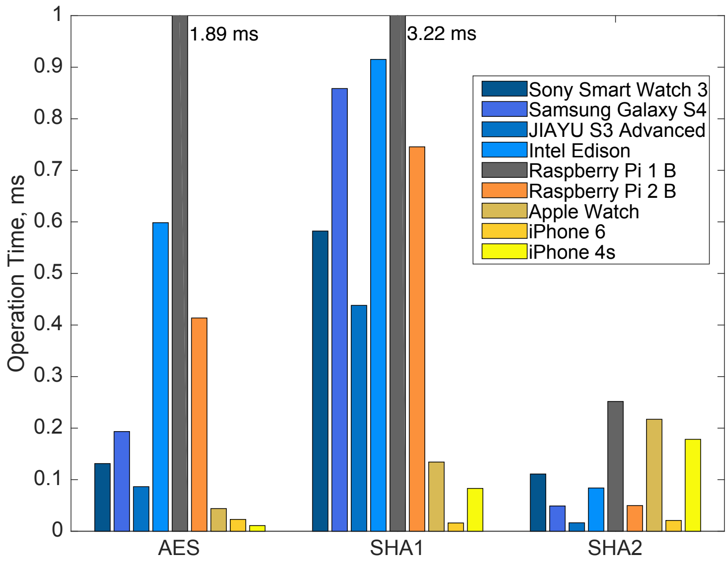


Fig. 3.5: Evaluation of execution times of pairing-based primitives on IoT devices

invalid devices based on dynamic accumulators and identification of attackers. These would be difficult to construct without pairing-based cryptography.

Inspired by that, we analyze and evaluate the most common personal / wearable devices – starting from the conventional smartphones to the embedded devices to smart watches – with a particular focus on their ability to execute both standard and advanced cryptographic operations. Taking into account such basic operation as hashing function or more advanced Secure Hash Algorithm (SHA), we evaluate the execution times of these primitives on all of the devices. The corresponding results are summarized in Fig. 3.5. We can conclude that for all of our test devices SHA1 and SHA2 are hardware optimized and mainly depend on the utilized equipment. As an example of the data encryption, we used Advanced Encryption Standard (AES) 128 cipher. The corresponding results still follow the execution time pattern of public-key cryptosystems and hashing functions for all of our devices. Moreover, as pairing-based cryptography primitives have not been rigorously evaluated on these devices so far, we also addressed this type of security functionality in [71].

Finally, we can conclude that modern IoT devices have already reached the computational power of a two-year old smartphone and, thus, IoT world fulfills the computational and security requirements of today. Constrained but powerful IoT devices, like Intel Edison, are designed so that the energy consumption is minimized. Due to that fact, the computational power is somewhat lowered, but this class of devices appears to be an attractive enabler for the required levels of information security.

4 USER EXPERIENCE AND ADOPTION OF FUTURE MOBILE SERVICES

4.1 General Background

Regardless of the type of service offered to the end users, their satisfaction is an indicator of adoption level of such service. This principle is even more critical in highly competitive environment as wireless networks [73]. Due to the aforementioned constantly increasing amount of mobile data traffic and its high diversity, network operators and service providers are already facing to a very difficult issue how to balance their CAPEX and OPEX while continuously providing satisfactory level of user experience.

Traditionally, network performance monitoring based on existing standards has been focusing on technical Key Performance Indicators (KPIs). However, traditional QoS model and parameters may not be sufficient to address new challenges imposed by emerging 5G applications and services and therefore it is more important to focus on user opinion, referred as QoE, directly. Service delivery in 5G should account for the sheer diversity of existing and emerging use cases as well as for the vast variety of demands per service type. These requirements would only be addressed by a shift from system-centric to user-centric architectures [7]. As a matter of fact, the QoE mechanisms need to be directly integrated into the 5G ecosystem to enable efficient management of network resources to meet applications' requirements. Such network setup is introducing the end user (does not matter if human-user, e.g. consumer of online video streaming service, or device-user, e.g. heating system actuator) as the logical epicenter of 5G architecture.

However, QoE is highly subjective and influenced by variety of factors (ranging from environmental, via content-based and user related, up to network-based) at the same time, thus it is not trivial to integrate all user-centric demands within the complex 5G-IoT ecosystem. For further QoE improvements, network and service management need to evolve together by exploring advances in automation, cognitive operations and big data. Moreover, mapping of the required services to the best possible resources and frequency, SDN and cloud technologies should be advantageous [74].

Growth of subscriptions, advertisement-based business models and content delivery are fueling almost exponential increase of video-streaming traffic in mobile broadband. It is expected that Over-The-Top (OTT) streaming services like YouTube or Netflix will surpass television in terms of number of viewers [75]. However, Internet video ecosystem lacks standardized quality measurement techniques. Traditional QoS metrics, comprising of packet loss, loss rate, network delay, PSNR and round-trip-times are now considered not effective for video over mobile Internet. Existing evaluation methods and tools usually consider only some factors of the network layer and application layer, rarely take into account the impact of user behavior on UX. In addition, they usually focus on the quality of video itself, not evaluating a complete mobile video service consumption process. Hence, the evaluation results have some deviation from the actual quality of the UX [76].

Besides estimating current QoE perceived by end users, the network operators are also requiring appropriate tools to anticipate the level of users's satisfaction with specific service under certain network conditions. Such information would help to distribute the network resources in more efficient manner and thus provide overall higher performance of communication system. The academia and industry as well have been working on this issue heavily during last several years. Nevertheless, it has been proven that the development of QoE prediction model providing sufficient accuracy, addressing the broad spectrum of personalized application criteria and being simple and fast enough to implement on-fly analysis within the future generations of wireless networks, is nearly impossible with current mindset. Therefore, also the user experience domain will require a notable change in design of QoE algorithms which

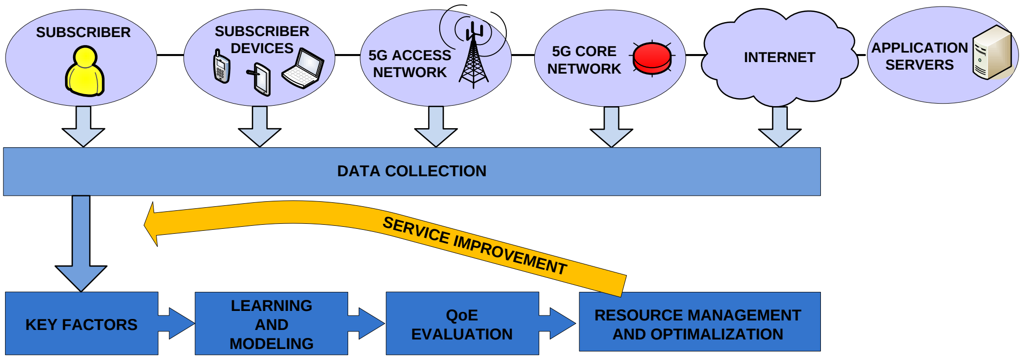


Fig. 4.1: QoE evaluation and modelling framework

need to be integrated into all 5G-grade technologies and services from very beginning. The high level of user satisfaction is a crucial indicator of usability and adoption of any emerging technology and so directly impacting the overall success of 5G vision.

Following this, when evaluating and/or predicting the QoE, we should not only comprehensively consider network layer, application layer, service layer and user-level factors, but also expand the sample size and use data mining algorithms to better analyze the relationship between all the factors to build a personalized and accurate QoE model. More sophisticated and advanced learning techniques should be considered to further improve the accuracy of QoE. The generic proposal of such QoE modelling framework expected within the 5G networks is shown in Fig. 4.1 [76]. It is important to mention that QoE is a constantly evolving process where the users' demands are changing (increasing) together with the improvements of the offered services. Due to this, it is crucial to be repeatedly collecting feedback from all involved functional elements and updating the structure of key factors accordingly. Then, the QoE models and related resource management and network optimization techniques should be upgraded as well.

4.2 Author's Focus and Contribution

This section provides insights into author's own research addressing the QoE issues of emerging mobile services. The described research is mainly based on four selected author's publications [77], [78], [79] and [80]. The particular interest was given to the research of QoE-related issues of two dominant mobile use cases: (i) mobile web services and (ii) HTTP-based video streaming services. What follows, is the summary on key contribution created by author and his team within this domain.

4.2.1 Modelling User Satisfaction with Mobile Web Services

As already indicated, cellular network operators are currently seeking for simple but accurate methods to measure and predict the levels of satisfaction for their customers using mobile web services. Even though the ultimate user demands are known to be influenced by multiple, difficult-to-quantify, factors, there is one clear trend - people require an increasingly higher quality of mobile Internet connection. For mobile industry, there is thus an increasing demand in effective QoE mechanisms that have to be integrated into the operators' traffic management systems, where QoE is typically defined as the user's overall acceptability of a service or application.

Inspired by this, we have decided to realize an extensive UX assessment study. The main goal of this campaign was to measure and collect the users' feedback while using his / her handheld device and consuming popular mobile web services like web browsing, file download and upload [77].

Recently ITU-T Rec. P.800 became standard for QoE evaluation of IP based services. However, P. 800 provides certain level of freedom and does not particularly address current trends of mobile web services and QoE assessment. Therefore, our work detailed in [77] proposed, to best our knowledge, very first methodology for evaluating the subjective UX while utilizing smart devices in mobile environment. Our main goal was to perform mobile QoE assessment as transparent as possible and create perfect illusion of "real usage" scenario. In order to achieve high level of transparency we have integrated an electronic questionnaire directly to the web environment. The next crucial task was to achieve accurate emulation of mobile network for all use case scenarios. Therefore, we set strict limits for maximal deviation of network parameters implemented in our solution.

Following our methodology, we have been systematically investigating user satisfaction variation under the most frequent scenarios reflecting the network performance levels, web contents and device. Such wide scale of conditions allowed us to discuss mutual relations between QoE and network performance parameters. Furthermore, this study introduced quality and saturation thresholds for mobile web service based on network performance indicators.

The selected network parameters varied the full range from clearly insufficient up to the superior in terms of network conditions. The wide scale of network arrangements were achieved with systematic changing of bit rates (BR) and initial delays. The initial delay is the time interval between the entering URL of required web page and starting of loading of this web page. From the user centric point of view, it is a waiting period needed for establishment of connection targeting the desired content. For example, if the initial delay is equal to five seconds, the test subject sees a "loading circle" within this period and then the web page starts loading.

Our QoE study was performed in the laboratory providing general viewing conditions for subjective assessments in home environment defined by ITU BT.500-13 and P.910. As evaluation metrics, the well-known five grade Mean Opinion Score (MOS) scale in combination with Absolute Category Rating (ACR) method were utilized [77].

The proposed assessment methodology was implemented into the QoE evaluation framework running as common website on selected smartphones and tablets. In order to achieve maximal relevance of obtained results we invited rather big sample of test participants - in total 108 persons took part in the study. Most of the experts were already experienced users of mobile web services using smartphones on daily basis [77]. The obtained results allowed us to present more dimensional QoE map for mobile web services, set quality thresholds and analyze differences between investigated contents under many conditions. Initial visual inspection of obtained results (see Fig. 4.2) clearly show the trend when quality ratings are rising with increasing BR and decreasing with the initial loading delay increase.

Moreover, the curves in Fig. 4.2 allow to define quality thresholds. The premium quality threshold refers to BR where a 3.7 MOS quality rating was achieved and the saturation threshold refers to BR, where quality rating is not any more increasing or achieve maximum quality rating or 4.5 MOS at five grade scale. The saturation quality threshold was achieved for zero delay at 512 kbps and 1024 kbps for three second initial delay. The premium quality threshold was achieved at 256 kbps at zero delay, at 512 kbps for one second initial loading delay and for 1024 kbps for three second initial loading delay. These values are very practical outcomes because we can clearly define quality saturation for tested scenarios and avoid web service over provisioning.

In order to fully utilize the obtained data set, we have applied a regression analysis tool and so developed new QoE prediction model to eliminate an over-provisioning in network resources and so manage cellular deployments more efficiently [78]. Our advanced QoE estimation model was extensively verified with appropriate statistical tools. The proposed model (see Eq. 4.1) follows from above introduced extensive QoE assessment and utilizes the BR together with the initial loading delay as well-measurable input parameters. Our key contribution is

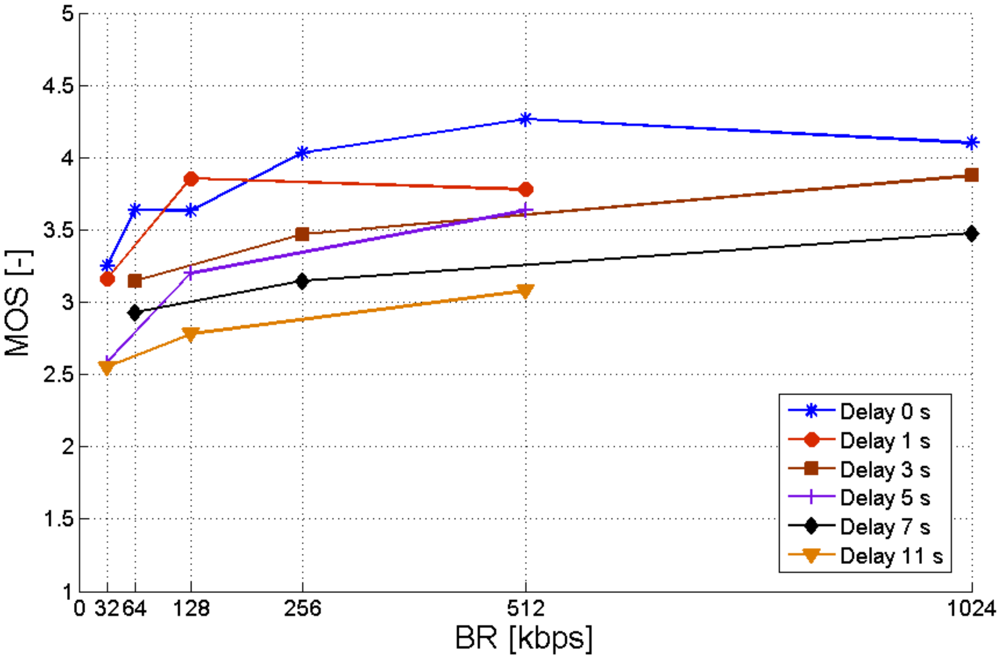


Fig. 4.2: The overall quality rating results for web scenarios

a low-complexity and easy-to-use QoE prediction model covering a wide spectrum of mobile data service conditions with high prediction accuracy. The model enables estimation of QoE saturation on a broad scale of real-life factors.

$$\overline{MOS} = \frac{(b-a)}{1+\tilde{c}_0\,(BR)^{-c_1-c_3 D}\,\tilde{c}_2^{D}} + a. \tag{4.1}$$

The key outputs are depicted in Fig. 4.3 which is comparing the slopes of three constructed surfaces and so demonstrates the similar raise of the average *MOS* with the increasing BR in all scenarios. The initial delay is not as essential for users who are involved in file uploading or downloading; the only meaningful predictor is BR and provided it stays high enough, the users are ready to wait. On the contrary, if a user is browsing the web, even minimal initial delay becomes disappointing, while even low BR suffice for the higher levels of satisfaction (see surface section for $D = 0$ in the foreground).

Recent developments in mobile data services yield systematic increase in network capacity and unanimous domination of web-based traffic. Meanwhile, user quality expectations are growing as well. Our work builds upon these important aspects and proposes an accurate and simple estimation model for the mobile QoE. In summary, our QoE model is very practical for accurate estimation of QoE overprovisioning which can be used for QoE-aware network design to avoid inefficient investments into the networking infrastructure.

4.2.2 Understanding Mobile YouTube Quality Expectations

Among the top streaming service providers, including Netflix and Hulu, YouTube has become the dominant, with 72 hours of video uploaded there every minute and over 4 billion video views per day. Thus, YouTube is globally largest online video sharing network nowadays which introduces certain issues for broadband mobile network providers. However, to make their customers satisfied, Internet service providers have to face this challenge while trying to

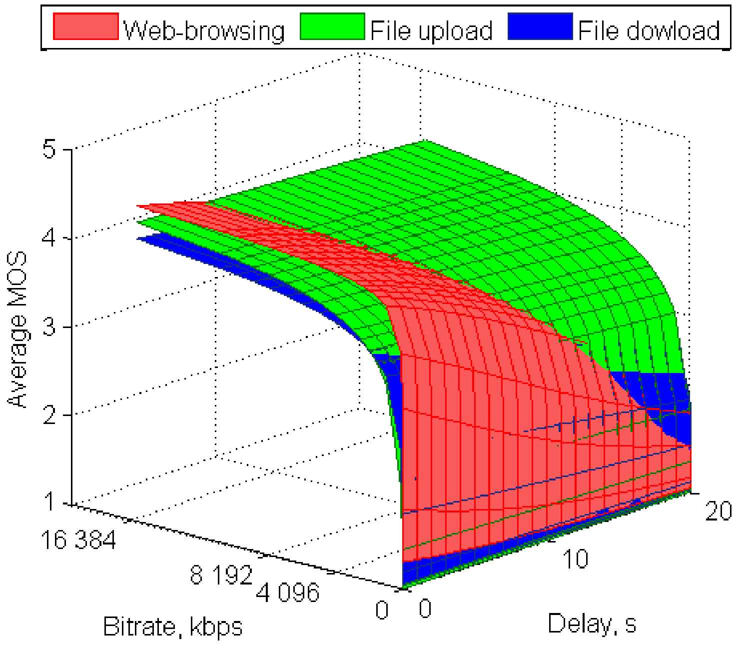


Fig. 4.3: Comparison of predicted average *MOS* surface depending on *BR* and *D* for web-browsing, file upload, and file download scenarios.

guarantee a high QoE level, which, in many cases, means additional investments to the network infrastructure. Therefore, it is now even more crucial than before to obtain statistically relevant UX assessments in order to find a reasonable trade-off between service QoE and investments.

Due to the rapid pace of development of mobile communications, the standardization is running behind and so community is lacking sufficient methodology to thoroughly evaluate QoE aspects of mobile video streaming services. Inspired by this and utilizing our experience with QoE study targeting web services, we have developed the methodology for subjective assessment of mobile YouTube service and similar [79].

Recent studies on YouTube QoE assessment methodologies and on QoE impact of buffering delay and stalling effects were considered in assessment design and selected use cases as well. On the other hand, the delay and stalling artifacts were introduced according to typical performance of broadband cell networks and in tight cooperation with mobile cell operator as well. The stalling effect, so-called freeze, as a common impairment in video streaming applications, is considered as a key influence factor in users perceived video quality. In order to address systematically the most critical influencing QoE factors, following variable types were taken into account:

- **Vary:** the factors that are of main interest within this project were systematically varied, i.e. experimental conditions are dedicated to representative characteristics of this factor (e.g., connections parameters).
- **Control:** factors, such end user device, which are expected to have a mediating impact on the QoE, were controlled. For example, in the sample specification, important variables like display size were distributed according to the target streaming service. This helped to achieve representative results, and by splitting the sample, possible effects on QoE could be retraced.
- **Constant:** some influence factors were kept constant, either due to the focus of the project, or due to standard recommendations (testing environment).

The selected variables show our methodological approach on different influencing QoE factors. In order to obtain high statistical relevance it was necessary to perform the study with

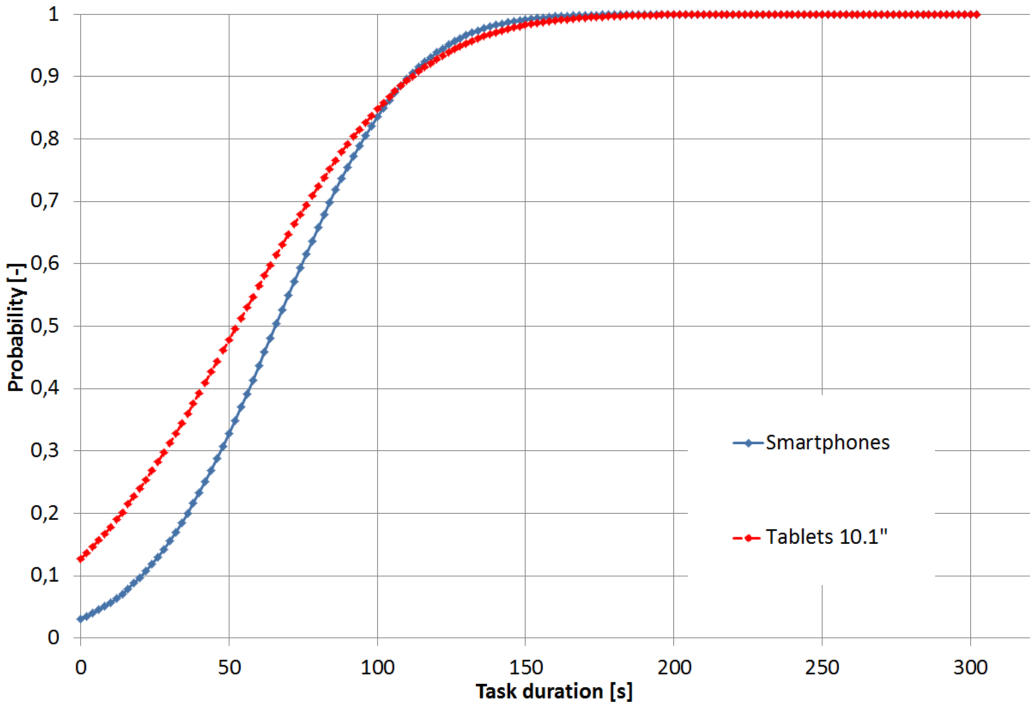


Fig. 4.4: CDF of real task duration

82 subjects. Therefore, our ultimate goal was to develop sophisticated QoE assessment and evaluation tool where the input parameters can be modified automatically and relevant results collected remotely without any test person's knowledge.

During our experimental study performed in laboratory conditions, the usage of YouTube service was not restricted or limited on defined scenarios. The test subjects could leave and evaluate the scenario in any time or stay until the end of the streamed sequence. Therefore, it was necessary to measure watching time duration of single sequence and consider only evaluations obtained after **minimal watching time of eight seconds**. The obtained Cumulative Distribution Function (CDF) of the real task's duration is introduced in Fig. 4.4. The CDF provides general overview how much time test persons spend on each task. Furthermore, it can be seen that 50% of test subjects left the smartphones' scenario after 66 seconds and after 56 seconds in case of tablets' scenario. This indicates that most of the test subjects spend significant time before the submission of task's assessment.

Two quality rating metrics were performed: ACR and acceptability rating. While the ACR provides fine-grained MOS results, it is not possible to validly answer the most fundamental question of QoE with this form of test: **Is the perceived quality acceptable, and when does it get unacceptable?** To address this gap, we performed also the acceptability ratings. This enables a more valid interpretation of the quality rating test results. Hence, besides the MOS evaluation, test subjects received simple binary question: *Were you satisfied with the provided quality? YES / NO*. The same test session compositions and successions as in the quality rating study were used for this acceptability assessment. The briefing phase was parallel to the ACR test and participants provided a voting via the same QoE assessment tool interface after MOS voting.

After processing the feedback collected from the experts interacting with mobile devices, we can conclude that the overall quality and acceptability at resolution 320x180 pixels are clearly insufficient (see Fig. 4.5). The considerable improvement is achieved at resolution 640x360 pixels. The video quality reaches the QoE saturation point at resolution 854x480 pixels. Moreover, it can be seen the relative quality decrease between optimal streaming conditions (no initial loading delay) and 5 and 10 second initial loading delays, but we can

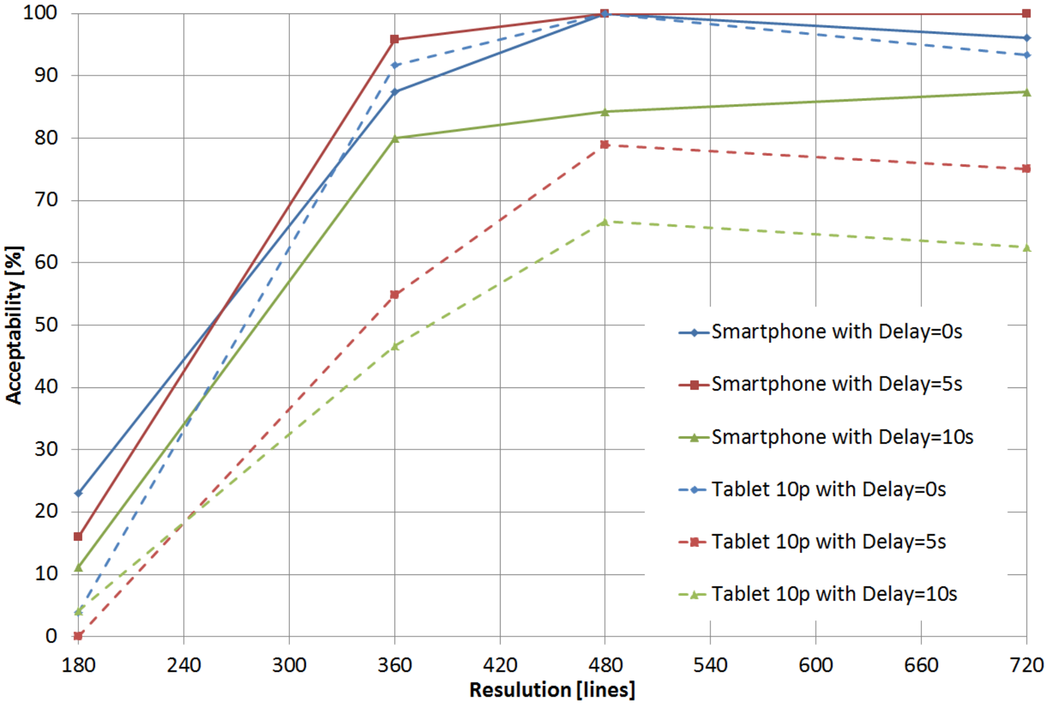


Fig. 4.5: Overall acceptability rating results vs. resolution

observe that the test subjects are not very sensitive to initial loading time up to 10 second duration. Both quality ratings show perfect correlations between quality and acceptability ratings. The smartphone use case has 97,2% and tablet use case has 99,1% pearson correlation. Finally, it can be seen than in identical scenarios, but using different devices, different ratings were obtained. Based on that, we found out that test subjects have higher QoE expectations from the tablet than from smartphone.

Clear understanding of YouTube users' demands and most influencing QoE factors is a serious challenge for mobile industry. On the top fo that, the pressing need for automatic QoE assessment solutions becomes even more pronounced for current and future mobile broadband networks, where over-provisioning is not economically feasible and poor UX simply translates to customer churn. Motivated by this, during last couple years, the community was trying to develop the said analytical solution, however, most of these models suffer from high complexity especially in terms of number of required input parameters, which, at the end, limits their application in real-world scenarios. Therefore, our developed model enables prediction of the expected YouTube users' subjective evaluation based on video resolution, initial loading delay, and stalling effect as these are easily measurable input parameters. The proposed solution is simple enough to be implemented on the operator side, but remains sufficiently accurate to help manage the mobile network in the way to keep customers' satisfaction at high levels and at all times which is also the key novelty of our work within this research area [80].

During one particular experiment (i, j), we measure the MOS denoted as $MOS_{ij}^{(k)} \in [a, b]$ for the fixed delay D_i and the resolution R_j for $k = \overline{1, K}$, where K is the number of measurements taken. Then, we average across the group of the obtained values as $MOS_{ij} = \frac{1}{K} \sum_{k=1}^{K} MOS_{ij}^{(k)}$. The resulting data (MOS_{ij}, D_i, R_j) may be employed as a training set for building a function of two primary variables $E[MOS] = \phi_{D,R}(D, R)$. Additionally, we include into consideration the aforementioned stalling effect by means of studying the *MOS degradation* for the selected fixed point (D_i, R_j). Within one experiment, the stalling effects are represented by their number N and the respective duration S, where the duration is assumed to be set equal for every stalling event. The inclusion of these new parameters introduces additional restrictions.

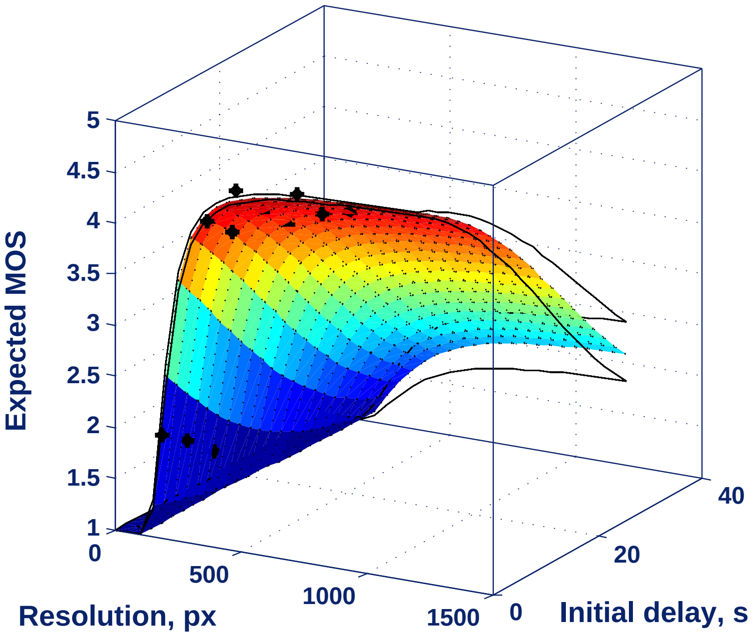


Fig. 4.6: MOS dependence on the resolution R and delay D: measurements (black dots) vs. predicted surface. The confidence interval is given by solid black curves.

As an output of our analytical approach, the resulting equation for the aggregated model comprising the component of the stalling quality degradation may be summarized as follows [80]:

$$MOS(D,R) = \left[\frac{(b-a)}{1+e^{-c_1 D - c_2 \frac{1}{R^2} - c_3}}\right] e^{-d_3 N^{d_1} S^{d_2}} + a. \tag{4.2}$$

The sample result is shown in Fig. 4.6, where the MOS dependence on the resolution R and delay D is introduced.

As already introduced, user experience became recently one of the key factors when evaluating the overall performance of network services and applications. This fact is even more pronounced for mobile multimedia services, including the on-line video streaming. Hence, the video-sharing websites, such as YouTube or Netflix, have already reached incredible levels of popularity, and thus cellular operators have to adopt their underlying networks to the resulting enormous amounts of traffic, mindful of its specific requirements. Therefore, the QoE-inspired network control mechanisms are highly demanded, and in this research we developed an analytical model allowing to predict the user experience for the popular YouTube application, which is based on our extensive research in subjective assessment of mobile services. The proposed methodology is built on top of several input parameters, including the initial delay, video resolution, and stalling effects, which are easy-to-quantify metrics from the mobile network operators' perspective. As a result, our developed QoE prediction model for YouTube enjoys very promising practical applicability.

5 CONCLUSION

This thesis targets various aspects of wireless communications and services forming together the future generation of cellular networks.

As first, the core motivation and 5G vision outline together with insights into the technical challenges and emerging technologies broadly addressed by the community are given in the Introduction. Subsequently, the scope of this thesis is highlighted through three pivotal sections.

The Section 2 continues with the discussion on particular contributions created by author within the domain of 5G enablers. This includes especially the techniques like transmission power control, network-assisted D2D communications and mobile data offloading.

In Section 3, one of the 5G use cases with the biggest impact on current society - IoT, is discussed. Within this domain, author's research deals mostly with an interoperability issue and development of unified communication and data sharing platform for different IoT applications.

In addition, the Section 4 provides an analysis of end user perception and adoption of emerging mobile applications and services. The key author's contribution in this area comprises of both: (i) design of methodology for evaluation of subjective user experience and (ii) development of QoE prediction model for the most critical multimedia applications.

All together, represents the author's three research angles comprehensively investigating the integrated 5G-IoT ecosystem. Each of those three chapters starts with general background where a summary of state-of-the-art challenges and issues is given. Followed by this, the subsections called "Author's Focus and Contribution" provide the compendium of author's authentic contribution within the specific domain solely based on the work conducted by himself and his colleagues.

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ABSTRACT

Wireless communications are perhaps the most critical element in the global Information and Communication Technologies (ICT) strategy, influencing many other industries. It is one of the fastest growing and increasingly dynamic sectors which has developed, just over last 40 years, from its very basic form, offering only voice service, to the current highly-advanced ecosystem merging a plethora of wireless technologies and applications and providing ubiquitous connectivity to all its users.

However, the society is currently standing on the doorway of new era of wireless technologies, so called 5th generation (5G), which is going to be implemented around 2020. During just few years, preliminary interest and discussions about 5G standard have evolved into a full-fledged research branch that has captured the attention and imagination of scientists and engineers around the world.

As already introduced by the community, 5G is supposed to become an end-to-end ecosystem to enable a fully mobile and connected society. It should empower value creation towards customers and industry, through existing and emerging use cases, delivered with consistent experience, and enabled by sustainable business models. To extend this definition, and as believed by many, the key goal of 5G networks is the *anytime & anywhere* support of data rates of up to several gigabits per second per user and hundreds of thousands of connections anticipated in emerging domain of Internet of Things (IoT).

To make this happen, cutting-edge technologies and innovations need to be developed to fulfill all those very strict, barely addressable by current means, requirements. Moreover, all of them have to comply with the very diverse demands that 5G-grade applications and services may have. Summarizing this, one of the main promises of 5G is to expand and even go beyond the possibilities what current mobile networks can offer. The 5G is expected to be first *true* communication platform unifying people and machines.

Inspired by this, the main goal of this thesis is to provide an overview of integrated 5G-IoT ecosystem and related technologies as emerging enablers of this revolutionary transformation happening in mobile world which is expected to deliver an ultimate and ubiquitous connectivity for any single human user electronic device. Particular focus in this work is given to the research of three different, however, highly relevant and interconnected, 5G aspects. At first, the solely technical discussion on 5G enablers is given, where the mechanisms like network densification, data offloading, device-to-device or mmWave communications are introduced. The second angle provides several insights into the IoT world which is expected to be vital thus natively supported by 5G systems. The last, but probably the most important, domain is dealing with the end user perception which is an essential indicator of overall success of this 5G vision.

All three aforementioned directions have been thoroughly investigated by author during last four years and the most significant results are introduced in this thesis. All together is providing a view on the 5G issues from a user perspective with a common goal to provide excellent quality of experience and adoption of future mobile services.