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Second Interim Report for the DFG Project FunkOFDMA

Florian Wamser[1], Dominik Klein[1], Phuoc Tran-Gia[1]

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[1] University of Würzburg
Institute of Computer Science
Department of Communication Networks
Am Hubland, D-97074 Würzburg, Germany
{wamser,dklein,trangia}@informatik.uni-wuerzburg.de

Julius-Maximilians-
UNIVERSITÄT
WÜRZBURG

Universität Würzburg
Lehrstuhl für Informatik III
Prof. Dr.-Ing. P. Tran-Gia

2nd Interim Report

to the proposal TR 257/28 (FunkOFDMA)

"Leistungsanalyse zur Funkressourcenverwaltung in zellularen OFDMA-Mobilfunknetzen"

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Applicants: Prof. Dr.-Ing. Phuoc Tran-Gia, Department of Computer Science, Würzburg
Dr. rer. nat. Dirk Staehle, Department of Computer Science, Würzburg

Proposal: **Performance evaluation for radio resource management in cellular OFDMA mobile networks**

Interim report for the third and fourth year of funding: August 1, 2011 – July 31, 2013

Summary: Orthogonal Frequency Division Multiple Access (OFDMA) is the technology of choice for today's mobile communication networks. The WiMAX wireless broadband standard uses an OFDMA-based physical layer specified in the IEEE 802.16 standard. 3GPP Long Term Evolution (LTE) uses OFDMA on the downlink. The performance of these systems crucially depends on intelligent methods for managing radio resources. These should exploit the theoretical capacity as much as possible while also taking system and network architecture as well as user and application demands into account. The interim report provides an overview of the work of the third and fourth year of funding. Several studies on application-aware resource management in the air interface of an OFDMA network were conducted. First, a packet scheduling approach based on client feedback was proposed that takes into account the application state of YouTube. With this approach, it is possible to temporarily prefer YouTube over other applications to ensure a good quality for YouTube users. Second, it was shown that the adaptation capabilities of Skype can be exploited for the scheduling to some extent. The automatic adaptation of Skype allows to tolerate certain bandwidth limitations for Skype users without significant decrease in quality for the user. Third, a simulation study on an application-aware scheduling for file downloads was performed with the aim, not only to enhance the quality of the application, but also to save energy at the end-user device. For comparison of these application-specific approaches, a comprehensive statistical evaluation was finally conducted with different ideas of application-aware scheduling according to different metrics and information. The outcome is a quantification of the benefits and the impact on the applications of different application-aware mechanisms.

The fundamental basis for the studies within this project phase, was an abstract modeling of YouTube, Skype, Dropbox, and web browsing. The models are required for the event-driven, time-variant simulation of the system consisting of users, applications, application behavior, TCP congestion control, and especially, packet scheduling and abstract data transmission at link-layer for LTE Release 8. The simulator was developed in cooperation with the Brno University of Technology, Czech Republic. Finally, a journal paper was published on general resource management approaches for YouTube in access networks which is based on several YouTube measurements for the modeling within a wireless access network. At present, it was not possible to measure and test these scheduling and resource management approaches in a commercial network, or to setup an own LTE communication network for tests due to the regulated radio licenses and the fact that many QoS functions are only described in specifications but not yet implemented by the vendors. For this reason, the measurements were performed in a wireless mesh access network.

2 General information

2.1 DFG reference number

TR 257/28-1, TR 257/28-2

2.2 Applicants

Prof. Dr.-Ing. Phuoc Tran-Gia
University Professor
Phone: (0931) 31-86630, Fax: (0931) 31-86632
Email: trangia@informatik.uni-wuerzburg.de

Dr. rer. nat. Dirk Staehle
Research Assistant
Phone: (0931) 31-86653, Fax: (0931) 31-86632
Email: dstaehle@informatik.uni-wuerzburg.de

2.3 Department

Julius Maximilian University Würzburg
Department of Computer Science
Chair of Communication Networks
Am Hubland, 97074 Würzburg

2.4 Topic of the project

Performance evaluation for radio resource management in cellular OFDMA mobile networks

2.5 Overall funding period

Beginning of funding: 01.06.2009
Already granted funding period for the project:
01.06.2009 – 31.05.2011 (physical layer resource management),
01.08.2011 – 31.07.2013 (application-aware resource scheduling)

2.6 Period covered by the report

Interim report for the second project phase, corresponds to the third and fourth year of funding:
01.08.2011 – 31.07.2013

2.7 List of important publications resulting from the second phase of the project

The most important publications: [1] application-aware resource scheduling proposal, [2] application-aware scheduling with respect to energy consumption, [3] statistical evaluation of application-aware scheduling approaches, [4] detailed analysis on general resource management strategies for YouTube

Peer-reviewed conference articles:

[1] F. Wamser et al. “Utilizing buffered YouTube playtime for QoE-oriented scheduling in OFDMA networks.” In: *Teletraffic Congress (ITC 24), 2012 24th International*. 2012, pp. 1–8.

[2] F. Wamser et al. “Investigation of different approaches for QoE-oriented scheduling in OFDMA networks.” In: *5th International Conference on Mobile Networks and Management (MONAMI)*. Cork, Irland, Sept. 2013.

[3] A. Blenk et al. “Dynamic HTTP download scheduling with respect to energy consumption.” In: *24th Tyrrhenian International Workshop on Digital Communications (TIWDC)*. Genoa, Italy, Sept. 2013.

Peer-reviewed journals:

[4] F. Wamser et al. “Using buffered playtime for QoE-oriented resource management of YouTube video streaming.” In: *Transactions on Emerging Telecommunications Technologies* 24.3 (2013), pp. 288–302.

Further publications related to the project, are described in detail in the following section.

3 State of the art and interim report for the research project from 01.08.2011 to 31.07.2013 (proposal name: FunkOFDMA)

3.1 State of the art

The aim of the project was the investigation of application-specific resource management approaches to quantify the benefit of certain information about applications. Since the submission of the renewal proposal at 31.03.2011, the following developments related to the project emerged in research:

There have been developments in the field of

1. 3GPP standardization,
2. application-aware approaches for the radio air interface,
3. application-aware approaches for the mobile core network,
4. user-centric and application-aware approaches for other wireless technologies,
5. Software-Defined Networking (SDN) as an enabler for application awareness,
6. many other approaches that deal specifically with video transmission.

The current research as well as standardization almost exclusively focuses now on 3GPP Long Term Evolution (LTE) or 3GPP High Speed Packet Access (HSPA). In particular, there are efforts in 3GPP towards application awareness and service differentiation. In general, the approaches can be distinguished according to the field of application: there are approaches that propose application awareness in the core network and there are approaches that utilize application awareness in the radio access. In the core network, rather larger aggregated flows are considered and certain QoS guarantees for a set of flows are enforced within the network to smooth and balance the load at the packet gateway. In the radio access in contrast, sometimes even individual users and their traffic are directly addressed to support a very accurate resource management and a wide range of applications. Here, it is relevant which applications the mobile user runs and how the scheduling can be customized according to the specifications. Overall, it is attempted to achieve end-to-end quality of service (QoS) differentiation using both approaches at the same time in the mobile network.

In the area of core network service differentiation, the following works deal with application awareness [21, 22]. In [21], for example, core-based traffic management is proposed that comprises a traffic detection function and a quality enforcement entity using a provider-defined set of rules. This fits to the efforts at standardization of 3GPP LTE. The following important elements are now defined within the LTE core network, Rel. 11 [23, 24]: (a) Traffic Detection Function (TDF), (b) Policy and Charging Rules Function (PCRF), (c) Application Function (AF), and (d) Policy and Charging Enforcement Function (PCEF). The AF offers applications a dynamic management that require dynamic policy and/or charging control. Executive element for the resource management is the PCEF at the packet gateway. The traffic is identified by the TDF by deep-packet-inspection or statistical packet analysis. Based on the information of the TDF, the PCRF decides what should be enforced in the network by the PCEF. In general, only the basic entities and the signaling for an application-related resource management are standardized in LTE. The exact definition of the rules in the PCRF, and how PCEF responds according to the rules within the network, has to be decided by the network operator.

With respect to application awareness in the air interface of a mobile network, the following publications are of particular interest [21, 25, 26, 27]. In [21, 25], for example, possible application level differentiation approaches are discussed, either assuming a single data bearer per user equipment (UE) or utilizing the potential of secondary bearers to prioritize selected applications. In HSPA the concept of the secondary packet data protocol (PDP) context exists, while dedicated bearers are defined for LTE/SAE. Each bearer will be treated according to the QoS profile assigned to it by the scheduler. This can be used to setup a specific bearer for applications with different requirements. In contrast, since the secondary PDP context is not well supported in legacy 3G/HSPA networks and devices, so-called in-bearer prioritization is proposed. There, user IP packets are inspected and marked in the mobile packet core by the TDF according to the operator's application and subscription

policies. In the radio access, the packets are then scheduled according to that mark in such a way that a certain QoS is guaranteed. In particular, video traffic is often subject of research in mobile networks. In [5, 6, 28, 29, 30], video traffic is considered and an appropriate resource management is suggested specific to this type of traffic.

For all types of communication networks, it has been shown that application awareness is particularly useful in the field of (a) access networks (e.g., air interface of mobile network, wireless access networks) [7, 8, 9, 31], (b) for a specific type of network that is under the control of the network provider (e.g., data centers, core network of mobile network) [21, 32], or (c) for a network designed for a particular application (e.g., dedicated networks or CDNs for video streaming) [8, 28, 30]. This is mainly due to the fact that for an effective use, additional information about the applications and optionally, the network are necessary to selectively perform the resource management.

Finally, there are papers that generally address the challenges and possible mechanisms of application-aware resource management [33, 34]. In [34], for example, a dynamic service-aware reservation framework is specified to enforce specific guarantees for certain applications in multi-layer networks. In [8], SDN-based application-aware networking is proposed with the help of deep packet inspection for YouTube video streaming. The authors demonstrate with a practical measurement the benefits of combining application-state information with SDN network control for network management. The users can benefit profoundly from this approach compared to purely QoS-based methods. Other papers in the area of application-oriented network management with SDN are for example [10, 35, 36]. In the field of QoE measurement and cross-layer QoE resource management, there are also new important publications that support an enhanced and user-oriented resource management [11, 12, 13, 14, 37]. To mention one publication by way of example, in [12], a generic formula is presented in which QoE and QoS parameters are connected through an exponential relationship. The formula relates changes of QoE with respect to QoS to the current level of QoE.

3.2 Progress report for the period between 01.08.2011 and 31.07.2013

For the second project phase between 01.08.2011 and 31.07.2013, the following objectives and work packages have been defined:

- *Work package 1*: Concluding studies on Fractional Frequency Reuse (FFR) and frequency-selective scheduling of the first project phase
- *Work package 2*: Application-aware scheduling for YouTube, Skype, and other applications with respect to different QoS service classes or application information
- *Work package 3*: Study of advanced scheduling ideas, e.g., look-ahead scheduler or application-specific resource restriction by scheduling or with the help of a resource manager that uses a strategy for limiting the resources.

The tasks of WP 1 and WP 2 have been successfully completed. The tasks of WP 3 were completed to a large extent.

Initially, the work on FFR was finished **(cf. Section 3.2.1)**. Thereafter, the evaluation of the application awareness was started. With the help of application models, a system-level simulator was implemented for the simulation of YouTube, Skype, web browsing, and file downloads **(cf. Section 3.2.5)**. Different practical strategies of application-aware scheduling were investigated after a discussion with a mobile network vendor. In particular, the following works were published: (1) prioritization of YouTube at low buffer level, cooperation with NEC Laboratories Europe [1], (2) negative weighting of Skype in favor of other users, and (3) application-aware scheduling for file downloads with the aim, not only to enhance the quality of the application, but also to save energy at the end-user device **(cf. Section 3.2.2)**. The idea for Skype belongs especially to WP 3 because Skype is not preferred in this approach, but its resources are limited, in order to gain resources for other users. In particular, it was also investigated to what extent existing QoS service classes of existing mobile networks can be used **(cf. Section 3.2.3)**. It turned out that it is difficult to make a global statement

about the quality of an approach for a mobile network when only a proof-of-concept is examined for one type of application. Because of this, more extensive studies were initiated as part of a Master's thesis and a paper [2], in which especially the impact on other applications was considered **(cf. Section 3.2.3)**. Thus, the effects of different scheduling strategies on YouTube, Skype, file downloads, and web browsing were evaluated with simulations at different load situations in a cell.

It should be further pointed out that an LTE physical layer was desirable for the simulation of the application-aware approaches due to the current development in research and standardization. The WiMAX link level simulation of the first phase of the project could not be fully used for research according to current mobile networks. Consequently, a cooperation with the Brno University of Technology has been initiated **(cf. Section 3.3)**. A researcher was invited to implement the physical layer data transmission according to LTE Rel. 8 for the system-level simulator to enhance the simulation. The work was successfully completed with the publication of the paper [1].

In the following, we describe in detail the results of this project phase.

3.2.1 Concluding studies to Fractional Frequency Reuse (FFR) and frequency-selective scheduling

In a student internship outstanding studies to FFR and frequency-selective scheduling were conducted. The influence of the packet size on the outage of users due to a) interference and b) the lack of resources was examined, since larger packets cause more resource-dependent user outage while smaller packages are rather responsible for interference-dependent outage. Finally, an optimal packet size for Soft Frequency Reuse with MCS optimization (interference reducing resource allocation, see interim report of former project phase 1) was determined.

3.2.2 Application-specific resource scheduling approaches

Packet schedulers in current cellular networks are based on hard QoS parameters, i.e., they either can provide the requested QoS or not. This differs for application-aware schedulers which may provide several thresholds for a certain, as well as, for a varying application quality. Accordingly, this flexibility can be used to exploit the temporal variability of the transmission channel to better support applications or compensate local load peaks by using fewer resources. In general, we have studied two possibilities to include specific application information in the scheduling process. First, an approach was developed for YouTube applications that temporarily prioritizes certain flows based on application state information [1]. Second, a guaranteed QoE-based scheduling was proposed that utilizes the flexibility of certain applications in order to introduce a fair QoE-based resource sharing among competing applications/users [2]. In addition, we investigated the influence of different scheduling approaches for HTTP downloads on application quality and the possibility, to save energy at the end-user device [3]. The lessons learned with respect to application-specific resource scheduling can be summarized as follows:

1. By introducing proactive prioritization of YouTube flows according to buffered playtime, QoE is significantly improved when competing with long file downloads. In this case, YouTube QoE is improved at the expense of the download duration, since for long downloads, this does not negatively influence download QoE [1].

2. The adaptation capabilities of Skype can be exploited for the scheduling to some extent. The automatic adaptation of Skype allows to tolerate certain bandwidth limitations for Skype users without significant decrease in quality for the user [2].

3. For adaptive applications like Skype, highly flexible QoE scheduling is contra-productive and results in very unstable situations due to the intrinsic automatic adaption. Instead, Skype sufficiently benefits from a static QoS service class with guaranteed QoS properties like small delay and fixed throughput [2].

4. Taking application-specific information into account for a sequential scheduling of downloads decreases energy consumption since average downloading time is reduced. This is achieved by utilizing the delay-tolerant nature of file downloads and by introducing a short waiting time of download requests [3].

Subsequently, we give a brief explanation of the different obtained results. In [1], we consider OFDMA access networks with YouTube users, and address the challenge of improving the QoE of a dedicated user by utilizing the buffered playtime of a YouTube video for scheduling. With this approach, scheduling is done according to the instantaneous throughput requirement of the video content, and not by the network by maintaining average QoS parameters. The YouTube client buffer level indirectly reflects the video encoding, i.e., the buffer level decreases when the video coding requires a high bitrate and, the other way round, the buffer level increases for a video with a low video bitrate. The scheduling incorporates the buffer level by explicit signaling in the scheduling decision by prioritizing YouTube users in case the buffer level is low and a QoE degradation is imminent. The results are evaluated with the 3GPP LTE system level simulator which implements a detailed model of the YouTube player, YouTube server, and TCP as well as wireless channel models. A buffering period of YouTube can be avoided at the expense of download time. Especially for long downloads, the overall QoE is improved since an increase of the download time can be tolerated for them and does not negatively influence the QoE [1]. In the paper, the scheduling algorithm is additionally evaluated with HTTP web browsing and a YouTube video, and we investigate the impact on web browsing users. The results show that web browsing users are only affected if the YouTube player runs out of buffered video data [1].

In [2], we particularly focus on Skype as one example of a network state adaptive application and investigate the possible gain due to a flexible QoE-based scheduling approach. The proposed QoE scheduler is similar to a proportional fairness scheduler, but instead of using a priority proportional to the possible throughput, a throughput inversely proportional to the current estimated QoE is used. A good application condition results in low priority while a bad condition results in high priority. According to the results, we can conclude that for applications like Skype, a smaller but more steady throughput is more efficient than a slightly higher but fluctuating one. The video encoding of Skype is very unstable for schedulers like the QoE feedback scheduler. The reason for this is the constantly changing bandwidth assignments with these schedulers. Hence, Skype benefits the most from a static service class with guaranteed QoS properties like small delay and fixed throughput.

Lastly, we studied in [3] the influence of different sequential scheduling approaches for HTTP downloads. Our proposed algorithms schedule downloads sequentially in order to avoid the parallel and competitive resource usage of multiple users. Thereby, the scheduling decreases the energy consumption and the average downloading times of the mobile devices. Although the overall download times do not increase significantly, waiting times are introduced. The results show how the scheduling affects the download time and the energy consumption. Although the algorithms do not increase the total available capacity of the access network, they have the potential to improve the situation for a subset of the users and, thereby, the average perceived quality and energy consumption of all users.

3.2.3 Statistical evaluations

After the studies of certain application-aware approaches for specific applications, a statistical analysis was done for a mix of applications, different schedulers, and different loads in the cell. In particular, the influence of different cross-layer scheduling heuristics on the application is examined for the air interface of LTE mobile networks. For this, not only the physical data transmission but also the application behavior is simulated in detail for Skype, YouTube, web browsing, and downloads. For each application quality, indicators are defined that provide information on the current performance of the application. The investigated scheduling approaches take into account detailed application information of different levels like the application type, the current status of the application, or the ability of an application to adapt to the network situation.

One mobile cell is simulated with the event-based simulator for LTE mobile networks. The evaluation is based on carefully chosen application quality indicators which provide a high QoE correlation: for YouTube the buffered playtime is used, since stalling is the main factor for a QoE degradation [15]. For web browsing the download time of the content is chosen while for file downloads the amount of downloaded data is considered as key quality indicator, c.f. [16]. For Skype the image quality and the steadiness of the video encoding are used.

The statistical evaluation was done for three different scenarios, namely a moderately, highly, and overloaded cell. To obtain statistically relevant results, 100 runs were conducted for each combination of scheduling discipline and scenario. The lessons learned with respect to the specific applications and scheduling disciplines are as follows:

1. File downloads are flexible applications and a certain delay or a low download throughput can be tolerated. Therefore, a more moderate behavior of the scheduler with respect to file downloads is desirable to gain resources for other applications.
2. Service class schedulers, which do not use detailed information about the web browsing users, show significant advantages in the average page loading times over the proportional fair scheduler. This benefit is gained by the restriction of the Skype users.
3. While the stalling probability increases with a larger number of users in the system, the use of a specific application-aware scheduler has no significant impact on the results. All application-aware schedulers result in similar stalling probabilities for all three scenarios and achieve much lower stalling probability than the proportional fair scheduler.

Generally considered, the evaluation of the application-aware schedulers in comparison to the state-of-the-art proportional fair scheduler demonstrated that application awareness improves the overall situation of the applications in the network. However, there are different results for different applications. For example, the YouTube application has achieved useful results with a scheduler with QoE feedback because the latter can tolerate dynamic changes in the bandwidth due to the video buffer. The Skype application in contrast does not require such a scheduling. For Skype video the QoE scheduling results in a very unstable situation due to the automatic adaptation. In contrast, Skype can benefit from a static service class with guaranteed QoS properties. Overall, the results demonstrate that basic knowledge about the application conditions can improve the scheduling process.

3.2.4 Basic research regarding application awareness

The fundamental basis for the studies within this project phase, was an abstract modeling of YouTube, Skype, Dropbox, and web browsing. The models are required for the simulation of the mobile system.

The following points have been achieved within the project:

1. For YouTube, the behavior of the Flash player and the content streaming server in the Internet has been analyzed and modeled.
2. For the YouTube Flash player, several important parameters have been identified: stalling threshold, initial playback threshold. Both depend on the buffer level.
3. The behavior of the content server was investigated to identify the flow control of YouTube.
4. For Skype, the adaptation behavior was measured under various network conditions. The adaptation behavior of Skype was identified as follows: Skype not only responds to packet loss by increasing redundancy in packets but it also adapts frame rate, image quality, and resolution on packet delay. Skype initially switches down the frame rate and increase this gradually again. If necessary, the image quality is downgraded as a next step. If the change of the frame rate and the image quality does not help, the resolution is ultimately reduced.
5. The models for web browsing and file downloads, were taken from [17] and parameters such as content size were updated by measurements and a literature study.
6. The behavior of Dropbox as a popular Internet file storage solution was examined at the packet level [18].

The proposal of this project phase, in particular, calls for investigation of application-aware resource management approaches for YouTube. Therefore, a study on possible resource management options was carried out as part of a bachelor thesis. In the resulting journal paper, different resource management mechanisms were proposed and evaluated to improve the Quality of Experience (QoE) of YouTube users [4]. Here, the following was achieved:

1. There are in total two options for a resource management of applications in order to improve the perceived quality at the end user or to balance the network load: a) resource management

in the network and b) the control or management of the application itself. The latter means for YouTube to selectively adapt the playback quality, which is possible through the provided YouTube API of Google. The adjustment on the video player to another quality level leads to a reasonable quality for the user (cf. MPEG Dash) and has also a significant impact on the network traffic.
2. In the journal paper, application-aware content prioritization was compared with a custom Internet gateway selection for multi-homed networks and a selective change in playback quality.
3. Network resource management and service control can be combined to obtain a holistic resource management. It has been shown that the following algorithm works in a meaningful way: As long as the problem can be solved by the network, only network resource management is used. The resource management within the network is used to balance resources and prioritize important content streams. If the load in the network is too high, the service control should be used to reduce the load of the services on the network. If there is still overload in the network, admission control must be carried out.

At present, it was not possible to measure and test these resource management ideas in a commercial mobile network, or to setup an own LTE communication network for tests due to the regulated radio licenses and the fact that many QoS functions are only described in specifications but not yet implemented by the vendors. For this reason, the measurements were performed in a wireless mesh access network.

Furthermore, a demonstration at IEEE Infocom 2013 was presented in the context of another project at the University of Würzburg [19]. For the demonstration some of the ideas mentioned above were implemented and evaluated. The project benefited from this cooperation and the obtained results.

3.2.5 LTE simulation

The simulation, which was implemented during the project, is an event-based system-level simulation of a single LTE cell with the possibility of performing a precise packet scheduling in downlink direction. The physical data transmission is performed on the basis of precalculated link-level curves for packet error and goodput from separate simulations with the LTE Downlink Link-Level Simulator of the Brno University of Technology. It implements a complete signal processing chain for the traffic channel. PHY and MAC functions are implemented according to LTE release 8 specified in [38].

Based on this physical simulation a complete system model is implemented with TCP transport protocol and application layer. TCP Cubic with congestion control, error detection and flow control can be simulated for each user to obtain realistic scenarios even in overload situations. The propagation model for the data transmission consists of path loss, shadow fading, and multipath fading. Inter-cell interference from other cells is not considered. Path loss can currently be calculated according to the Winner II urban macro-cell model [39].

At application layer, the following applications can be used: YouTube, Skype video call, file download, and web browsing. For YouTube, the Flash player is simulated as well as the flow control of the YouTube content server in the Internet to the mobile user. For Skype, especially, the adaptation mechanism is implemented. On the packet level, a queue based scheduling at the base station is simulated. The packet scheduler chooses the packets from the user queues according to the scheduling algorithm and passes them to the resource allocator. The resource allocation then selects the appropriate modulation and encoding based on the link-level curves depending on the users channel and places it in the frame.

3.3 Communication with industry and research institutes

During the entire project phase, various aspects were discussed with existing scientific contacts from the prior project phase:

- NEC Laboratories Europe, Andreas Maeder
- Wireless Communications Lab, Intel Corporation, US, Jing Zhu

- Wireless Communications Lab, Intel Corporation, US, Rath Vannithamby
- Brno University of Technology, Jan Prokopec
- University of Alcala, Madrid, Spain, Jose Manuel Gimenez-Guzman
- Technical University of Munich, Wolfgang Kellerer
- Hotzone GmbH, Berlin, Klaus Heck
- Blekinge Institute of Technology, Sweden, Markus Fiedler

Moreover, the active discussion with NEC Laboratories Europe, NTT DoCoMo, and Brno University of Technology resulted in a joint paper [1] presented at the 25th International Teletraffic Conference. In preparation for the paper, Jan Prokopec visited the University of Würzburg to develop the link level modeling of LTE Release 8 together with the researchers at the department. He was mainly involved in the development of the link level LTE simulator at the Technical University of Vienna [40]. During his stay at the University of Würzburg, he included the uplink part in the system level simulator available at the department to enable more realistic simulations of LTE access networks.

During another cooperation, Jose Manuel Gimenez-Guzman from the University of Alcala joined the department to conduct LTE evaluations along with QoE studies. At the department, he profited from the knowledge collected in this project. The joint paper tackles the trade-off for video provider in LTE networks between smartphone energy consumption versus wasted traffic [20].

3.4 Collaboration in research associations, conference organization

Since 2001, the department is actively participating in the VDE/ITG-Section 5.2.4 ”IP and Mobility” and in the VDE/ITG-Section 5.2.1 ”System Architecture and Traffic Engineering”. Addressed topics are network architectures and quality of service as well as traffic steering mechanisms and the modeling of network traffic and the network system in general. In addition, the department is also working in the area of wireless network planning and traffic characterization. On the European layer, the department is participating in various European cooperation in Science and Technology (COST) actions. The COST ICT action IC0906, wireless networking for moving objects, coordinates the development of new algorithms, techniques, protocol models and tools that will facilitate the integration of moving objects into pervasive and ambient communications. COST ICT action IC0703, traffic monitoring and analysis (TMA), coordinates both research groups and network operators active in the field of TMA, promoting the development of novel techniques and focusing the research efforts towards commonly recognized problems, thus driving the research towards real-world applications. COST ICT action IC1303, algorithms, architectures, and platforms for enhanced living environments (AAPELE), addresses the issue of defining software, hardware, and service architectures for ambient assisted living (AAL). Lastly, COST ICT action IC1304, autonomous control for a reliable Internet of services (ACROSS), wants to create a European network of experts aiming at the development of autonomous control methods and algorithms for a reliable and quality-aware Internet of services.

In 2011 and 2012, two workshops on the topic of future Internet were hosted at the University of Würzburg. The 11th and 12th Würzburg Workshops on IP addressed various network related topics and with respect to wireless networks, topics such as wireless broadband access, 802.16x, LTE, LTE-Advanced, and IMT-Advanced networks as well as mesh networks and wireless network management were discussed. Moreover, a summer school on the topic of modeling and analysis of novel mechanisms in future Internet applications was organized in 2012 at the University of Würzburg within the context of the European Network of Excellence project. Besides that, a crowdsourcing workshop was held at the department to foster cooperation within the area of crowdsourcing applications. In addition to the events hosted at the University of Würzburg, the department was also participating in the organization of various international conferences, workshops, or particular conference tracks or sessions. Examples are the Australasian telecommunications networks and application conference (Atnac 2013), the ITC specialist seminar on energy efficiency and green networking (SSEEGN 2013), the special session QoE for web and cloud applications at QoMEX 2013, or the track on smartphone applications for ubiquitous and pervasive computing at IMIS 2012.

3.5 Qualification of young researchers in the context of the project

In addition to the applicants, the DFG-funded researcher, and the DFG-funded student helper, other members of the department also contributed to this project. Furthermore, selected parts of the research were done by students within their Bachelor, diploma, or Master's theses. The following theses were done within the two years related to the project:

1. Michael Denkler: Application-aware scheduling in cellular OFDMA networks for YouTube and Skype.
2. Andreas Blenk: Application-aware resource management in wireless mesh networks.
3. Sebastian Deschner: Performance comparison of application-aware resource scheduling with respect to the channel behavior.
4. Christian Moldovan: YouTube traffic characterization: impact of flow control mechanisms and Internet-wide traffic distribution.
5. Florian Mayer: Evaluation of different application-aware approaches for YouTube

The conducted research and the obtained results are planned to be used within a PhD thesis.

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Publications of Chair of Communication Networks
Peer-reviewed conference articles and journals:

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