Digital Dividend: Potentials and Limitations of Mobile Broadband Access

Helge Lüders and Peter Vary

Institute of Communication Systems and Data Processing (ind)
RWTH Aachen University, Germany
{lueders|vary}@ind.rwth-aachen.de

Zusammenfassung: *Diese Arbeit zeigt Potenziale und Grenzen heutiger und künftiger Mobilfunksysteme zur flächendeckenden Versorgung mit breitbandigen Datenzugängen auf. Der Fokus liegt dabei auf der aktuellen Version (Release 8) des UMTS-LTE-Mobilfunk-Standards mit je einer Sende- und Empfangsantenne. Es wird gezeigt, dass dieser bei Nutzung von 20 MHz Frequenzbandbreite und mit den gegebenen Parametern zu Kanalkodierung und Modulation einem einzelnen Nutzer Spitzennutzerraten zwischen 2,8 Mbit/s am Zellrand und ca. 80 Mbit/s in der Nähe der Sendeantenne zur Verfügung stellen kann. Der durchschnittliche Zelldurchsatz gemittelt über gleichmäßig über die Fläche der Funkzelle verteilte Nutzer beträgt bis zu 39 Mbit/s. Diese Werte skalieren linear mit der zur Verfügung stehenden Frequenzbandbreite. Durch Mehr-Antennensysteme und intelligente Interferenz-Managementalgorithmen lassen sich diese Werte noch steigern. Mithilfe der abgeleiteten Grenzen lässt sich zeigen, dass theoretische kapazitätserreichende Systeme mit* 4×4*-Antennenkonfiguration und idealer Interferenzauslöschung durchschnittliche Zelldurchsätze > 1 Gbit/s erreichen können.*

Summary: *This work highlights potentials and limitations of current and future mobile radio systems for area-wide mobile broadband access. The focus is on the current Release 8 of the UMTS LTE mobile radio standard implemented as single-antenna system. It is shown that, for the given parameters, user peak rates between 2.8 Mbit/s at the cell edge and approx. 80 Mbit/s near the base station can be achieved by single users utilizing 20 MHz frequency bandwidth. The average cell goodput of an arbitrary number of uniformly distributed users in a radio cell reaches up to 39 Mbit/s. These figures scale linearly with the available frequency bandwidth and can be increased using multiple-antenna systems and intelligent interference management algorithms. With the derived bounds it is shown that theoretical capacity achieving* 4×4 *multiple-antenna systems with ideal interference cancellation could achieve an average cell goodput > 1 Gbit/s.*

1. Introduction

The current *Breitbandatlas 2009_01* [1] states that broadband access (download rates > 1 Mbit/s) is available for 93.43 % of the population in Germany. This figure is based on the availability of different broadband access technologies including DSL, cable modem, fibre, fixed or mobile broadband access. To cover the remaining so-called *white spots* fixed and mobile radio access systems have recently caught the attention of the public and the government [2].

This contribution points out the potentials and limitations of current and future mobile radio communication systems for area-wide wireless broadband access. The focus is on the potential of UMTS *Long Term Evolution (LTE)* which is considered the first step toward the goals set by the Next Generation Mobile Networks (NGMN) Alliance for fourth generation (4G) mobile networks. Additional benefits are expected from new carrier frequencies having their origin in the so-called *digital dividend*: Frequencies become available for telecommunication due to the transition from analog to digital TV which requires less radio spectrum.

This work has been supported by the UMIC Research Centre, RWTH Aachen University.

2. Physical Layer Performance

The current Release 8 of the UMTS LTE standard [3], [4] features a flexible physical layer employing turbo channel coding, rate-matching by adaptive puncturing or repetition of encoded bits, *hybrid automatic repeat-request* (HARQ), a choice of complex signal constellations (BPSK, QPSK, 16QAM, and 64QAM all with Gray mapping), and cyclic prefix *Orthogonal Frequency Division Multiplexing* (OFDM) with a bandwidth dependent number of subcarriers for downlink modulation. The choice of the modulation and coding scheme for each individual user, i.e., the code rate and complex signal constellation, is left to the scheduler based on the instantaneous channel conditions and the current load of the radio cell.

Based on the UMTS LTE physical layer specifications, simulations have been conducted to determine the achievable goodput $\mathcal{G}$, i.e., error-free data throughput for different combinations of code rates r and complex mappings assuming a single-antenna system (*single input single output, SISO*). In this work UMTS LTE code rates are restricted to $r \in \{1/3, 1/2, 2/3, 3/4, 4/5\}$. QPSK, 16QAM, and 64QAM can be selected for complex mapping and up to 4 transmissions (one initial transmission and up

ISBN 978-3-8007-3225-8

to 3 retransmissions triggered by the HARQ scheme) are possible. 2100 resource elements (REs $\hat{=}$ complex baseband samples), i.e., 25 resource blocks (RBs) are assumed per 5 MHz frequency bandwidth and 0.5 ms time slot. The resulting envelopes for all combinations of coding and complex mapping depicted in Fig. 1 represent the achievable peak goodput $\hat{\mathcal{G}}$ of a single user utilizing all REs of a UMTS LTE radio cell with frequency bandwidth $\Delta f = 20\,\text{MHz}$ for different channel models and channel qualities.

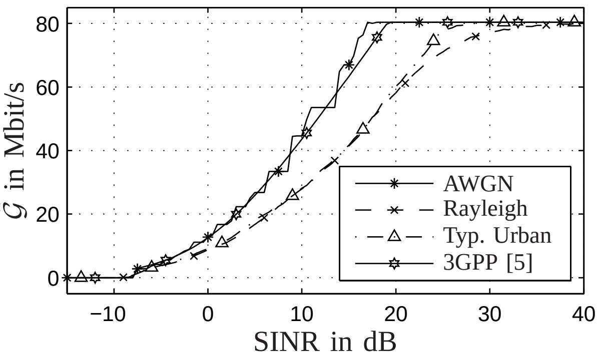


Fig. 1. Ideal peak goodput $\hat{\mathcal{G}}$: single user case, UMTS LTE, adaptive coding and modulation, different channel models, perfect channel knowledge, $\Delta f = 20\,\text{MHz}$.

These channel qualities are given as *signal-to-interference-and-noise ratio (SINR)* and are generally determined by the location of the user in relation to the base station (BS). A user near the BS will experience a good channel quality which allows for the error-free decoding of transmitted data after the initial transmission at the highest possible code rate $r = 4/5$ for the highest order signal constellation 64QAM (6 bit per RE) which, using all 8400 REs per 0.5 ms time slot, leads to a peak goodput of $\hat{\mathcal{G}} = 80.64\,\text{Mbit/s}$. Near the cell edge at low SINR values, 4 HARQ transmissions are necessary at the lowest considered code rate of $r = 1/3$ with QPSK (2 bit per RE) leading to a peak goodput of $\hat{\mathcal{G}} = 2.8\,\text{Mbit/s}$.

The best performance is achieved for the frequency-flat non-time varying *additive white Gaussian noise (AWGN)* channel model ($*$) which matches well with the reference given in the UMTS LTE standard [5], thus verifying the results of the physical layer simulations. The doubly selective *typical urban* channel model ($\triangle$) from [6] and the frequency flat time varying Rayleigh fading channel model ($\times$) which model real-world conditions of mobile radio channels in more detail lead to expected degradations regarding the peak goodput performance.

3. System-Level Parameters

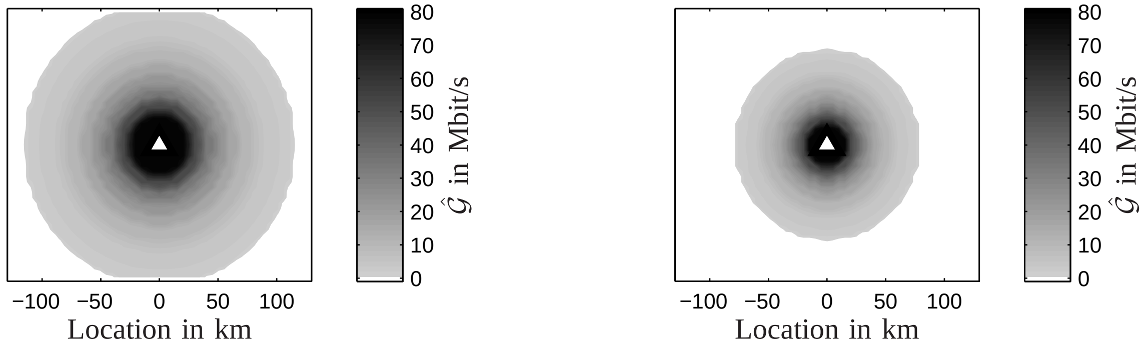
On top of these physical layer simulation results, system-level simulations of the downlink (transmission from the BS to the user) are performed to evaluate the potentials and limitations of UMTS LTE concerning the coverage and capacity of a radio cell. Therefore, the best case from Fig. 1, i.e., the AWGN channel model is considered for the remainder of this work. The system-level simulations consider the different SINR values within a radio cell by accounting for (a) the path loss affecting the data carrying signal transmitted from a central BS, (b) the interfering signals received by the user from BSs of adjacent radio cells, and (c) the thermal noise power inherent to any receiving device.

Path loss and interference strongly depend on the position of the user within the cell, but also on the carrier frequency f_0. Two carrier frequencies are considered: $f_0 = 0.8\,\text{GHz}$ representing the frequencies from the digital dividend and $f_0 = 2.0\,\text{GHz}$ representing carrier frequencies of current UMTS deployments. The employed frequency bandwidth of $\Delta f = 20\,\text{MHz}$ represents the largest frequency bandwidth supported by UMTS LTE Release 8. The receiver noise varies with the frequency bandwidth and is determined by $-174\,\text{dBm/Hz} \cdot \Delta f = -101\,\text{dBm}$. A radio cell within a network is considered to be hexagonal with radius $D \in \{0.2\,\text{km}, 10\,\text{km}\}$ and an omnidirectional transmitting BS in the center. This serving base station is surrounded by six interfering BSs at distances $d = \sqrt{3} \cdot D$. All BSs transmit at the same transmit power of 46 dBm and an additional gain of 15 dB is taken into account. The path loss models considered in this work are chosen according to the cell sizes. Small radio cells with cell radius $D = 200\,\text{m}$ represent an *urban micro-cell environment (UMi)* where the path loss is described by the COST-Walfisch-Ikegami-Model [7]. A radio network consisting of cells with radii $D = 10\,\text{km}$ represent a *rural macro-cell environment (RMa)* where path loss according to the model for urban environments from [5] is assumed.

The influence of the two considered carrier frequencies on the coverage of a mobile radio system is depicted in Fig. 2. Rural path loss is assumed in a single cell deployment, i.e., no interfering BSs are present. the maximum achievable goodput $\hat{\mathcal{G}}$ is directly determined from the location dependent SINR using the physical layer simulation results depicted in Fig. 1.

Obviously, a significantly better coverage is achieved with the carrier frequencies from the digital dividend represented by $f_0 = 0.8\,\text{GHz}$ in Fig. 2(a) compared to the frequencies from current UMTS deployments represented by $f_0 = 2.0\,\text{GHz}$ in Fig. 2(b). This leads to the conclusion that the frequencies from the digital dividend are an essential prerequisite for the fast area-wide coverage with mobile broadband access technology by deploying large radio cells.

ISBN 978-3-8007-3225-8



(a) Digital dividend: $f_0 = 0.8\,\text{GHz}$

(b) Standard UMTS band: $f_0 = 2.0\,\text{GHz}$

Fig. 2. Ideal peak goodput $\hat{\mathcal{G}}$: single user case, UMTS LTE, rural environment, different carrier frequencies, $\Delta f = 20\,\text{MHz}$.

4. UMTS LTE Capacity

The SINR at the cell edges of the considered *cellular* UMi and RMa environments is dominated by the interfering power from the adjacent BSs. This leads to very similar SINR and $\hat{\mathcal{G}}$ distributions within the considered radio cells independent of the carrier frequency f_0. Therefore, in the following only mobile radio systems operating at $f_0 = 2.0\,\text{GHz}$ are considered.

In practice, the REs of a radio cell have to be shared between all users of that cell. Considering uniformly distributed users sharing the REs equally, an average cell goodput $\overline{\mathcal{G}}$ can be calculated by summing up the location dependent user goodputs $\mathcal{G}$ of each individual user. In that way $\overline{\mathcal{G}}$ represents an average capacity of a radio cell. In the UMi environment, $\overline{\mathcal{G}} = 38.7\,\text{Mbit/s}$ is achieved for $\Delta f = 20\,\text{MHz}$ scaling linearly with the frequency bandwidth. In the RMa environment a slightly smaller value of $\overline{\mathcal{G}} = 35.2\,\text{Mbit/s}$ is observed. Again, these average cell goodputs are shared by all users of the considered radio cell.

To illustrate the distribution of the achieved user goodputs $\mathcal{G}$ within a radio cell, system-level simulations have been conducted in form of Monte-Carlo simulations. In each of 1000 Monte-Carlo iterations a predefined number of users represented by their user equipments (UEs) is randomly placed within the cell area of the serving cell. For each UE the individual SINR is calculated, all available resource elements are shared equally among UEs and the resulting goodput $\mathcal{G}$ of each individual user is recorded. After the final Monte-Carlo iteration, all individual goodputs are evaluated in form of a cumulative distribution function (CDF). This CDF indicates the percentage of UEs which achieve certain range of user goodputs. From the findings discussed before it can be assumed that the lowest user goodputs will be obtained by the UEs near the cell edge while the upper percentiles are achieved by UEs near the BS. A small slope of the CDF indicates a large variance of user goodputs, while a steep slope indicates less varying goodputs, i.e., a smaller goodput differences between UEs at the cell edge and UEs near the BS. The number of UEs and the available system bandwidth Δf are expected to have a linear effect on the user goodputs observed in a radio cell, because these parameters scale the number of available REs.

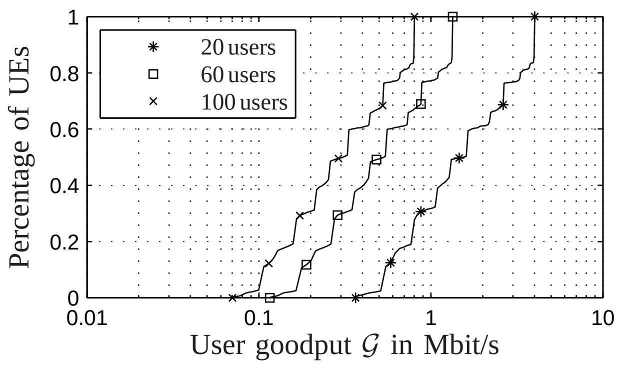


Fig. 3. CDF of user goodput $\mathcal{G}$: UMTS LTE, UMi, $f_0 = 2.0\,\text{GHz}$, $\Delta f = 20\,\text{MHz}$.

This expectation is confirmed by Fig. 3 which compares the CDFs of the achieved user goodputs for different numbers of UEs (20, 60 or 100) in a UMi environment with AWGN for $\Delta f = 20\,\text{MHz}$. As expected, all CDFs exhibit the same progression which proves the predicted scaling of resources. For 100 UEs ($\times$) the weakest 20 % (0 – 0.2 on ordinate) of the users, i.e., those at the cell edges, achieve goodputs of approximately 70 – 150 kbit/s while the strongest 20 % (0.8 – 1 on ordinate) of the users, i.e., those close to the BS achieve 700 – 800 kbit/s. If only 20 UEs ($*$) are present in the cell, these figures quintuple. It is observed that user goodputs at the cell edge and near the base station differ by a factor of more than 10.

The findings presented in this section have found to be in line not only with published results of simulations of other groups, e.g., [8], but also with the observations from different field trials.

5. Limitations of Mobile Broadband

Current research in the physical layer of mobile radio communications thrives at extending the per-

ISBN 978-3-8007-3225-8

formance to its limits while keeping the computational complexity as low as possible. For SISO systems the bound on achievable goodput for a certain SINR is given by the *Shannon limit*. To further increase the goodput, multiple-antenna techniques, i.e., *multiple input multiple output (MIMO)* systems, have been introduced. The first premium UMTS LTE transceivers will feature MIMO with up to 2 transmit and receive antennas. However, the goodput of MIMO systems is bounded as well. It has been shown that the goodput of $A \times A$ MIMO systems (A transmit and A receive antennas) is upper bounded by A times the Shannon limit [9].

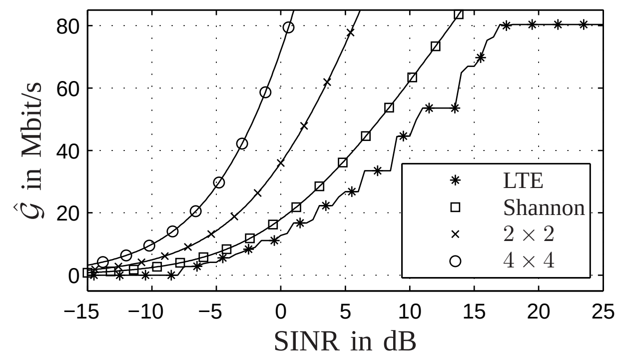


Fig. 4. Ideal peak goodput $\hat{\mathcal{G}}$: single user case, UMTS LTE and bounds for ideal capacity achieving systems, $\Delta f = 20\,\text{MHz}$.

The resulting bounds on the achievable peak goodput $\hat{\mathcal{G}}$ for SISO and MIMO transceivers based on OFDM modulation equal to UMTS LTE (equal time bandwidth product) are depicted in Fig. 4 and compared to the peak goodput $\hat{\mathcal{G}}$ of UMTS LTE in an AWGN environment. It is observed that UMTS LTE ($*$) achieves approximately 65 % of the Shannon limit ($\Box$), which results in similar peak goodputs at low channel qualities (-5 – 0 dB). The bounds for 2×2 and 4×4 MIMO systems ($\times$, $\circ$) are the doubled and quadrupled values of the SISO bound given by the Shannon limit.

To illustrate the limitations of future radio systems, theoretical transceivers achieving these bounds *(capacity achieving systems)* are considered in system-level simulations. The results for the determined average cell goodput $\overline{\mathcal{G}}$ for LTE and bounds on $\overline{\mathcal{G}}$ for SISO and MIMO systems in different cellular scenarios are summarized in Table I for $\Delta f = 20\,\text{MHz}$.

	UMi	RMa
SISO LTE	**38.7 Mbit/s**	**35.2 Mbit/s**
Shannon	60.1 Mbit/s	53.0 Mbit/s
2×2 MIMO	120.2 Mbit/s	106.0 Mbit/s
4×4 MIMO	240.4 Mbit/s	212.0 Mbit/s

TABLE I

IDEAL AVERAGE CELL GOODPUT $\overline{\mathcal{G}}$: UNIFORMLY DISTRIBUTED USERS, FULL INTER-CELL INTERFERENCE.

The major part of the capacity gains in terms of $\hat{\mathcal{G}}$ for the considered bounds is due to the arbitrary high number of transmitted bits per RE at high channel qualities. However, these bounds will hardly be achieved in practical systems due to computational complexity, physical implementation aspects and the mere physics of the radio channel.

Figure 5 depicts the CDFs of user goodputs $\mathcal{G}$ obtained from system-level simulations in a UMi environment with 20 UEs and $\Delta f = 20\,\text{MHz}$. Again, it is observed that UMTS LTE ($*$) performs fairly close to the Shannon limit ($\Box$). As opposed to the capacity achieving systems, the maximum user goodput $\mathcal{G}$ of UMTS LTE is limited by the maximum considered code rate of $r = 4/5$ with 64QAM modulation. The user goodputs of the capacity achieving systems scale with the number of antennas. Due to the large range of peak goodputs $\hat{\mathcal{G}}$ at the occurring channel qualities (cf. Fig. 4), the user goodputs at the cell edge and near the base station differ by a factor of more than 20.

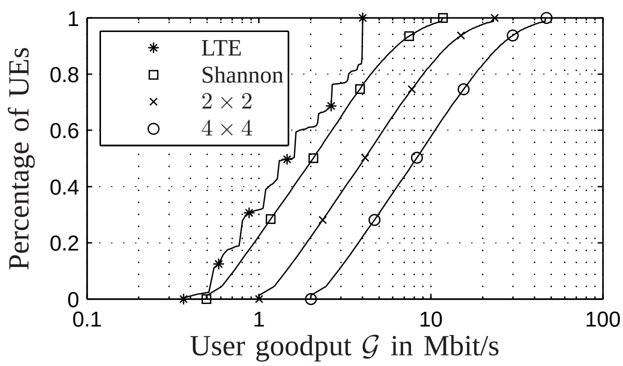


Fig. 5. CDF of user goodput $\mathcal{G}$: UMTS LTE and ideal capacity achieving systems, UMi, $f_0 = 2.0\,\text{GHz}$, $\Delta f = 20\,\text{MHz}$, 20 users.

This illustrates that a major issue in cellular environments of future mobile radio systems will be the interference from adjacent cells, which can be handled by concepts like *(iterative) interference cancellation (IC)* or *cooperative MIMO*. The concept of IC is incorporated into the system-level simulations by omitting the inter-cell interference caused by adjacent BSs when calculating the SINR. In that way, ideal IC is assumed which can also be interpreted as the lack of interferers, i.e., as a single cell deployment in a rural area (cf. Fig. 2). In this interpretation, no cell edges in terms of ideal handover locations exist. In such a single cell scenario all users are considered to be located within a circle of radius D around the BS. Obviously, with the lack of inter-cell interference, the propagation characteristics for the different carrier frequencies will influence the results. To illustrate potentials of an optimum setup, the more advantageous carrier frequency from the digital dividend, $f_0 = 0.8\,\text{GHz}$, is considered. With

ISBN 978-3-8007-3225-8

the assumption of ideal IC and $\Delta f = 20\,\mathrm{MHz}$, the average cell goodput $\overline{\mathcal{G}}$ is determined for LTE and the capacity achieving systems and summarized in Table II.

	UMi	RMa
SISO LTE	80.3 Mbit/s	80.3 Mbit/s
Shannon	411.6 Mbit/s	245.6 Mbit/s
2×2 MIMO	823.2 Mbit/s	491.2 Mbit/s
4×4 MIMO	1646.4 Mbit/s	982.3 Mbit/s

TABLE II
IDEAL AVERAGE CELL GOODPUT $\overline{\mathcal{G}}$: UNIFORMLY DISTRIBUTED USERS, IDEAL INTERFERENCE CANCELLATION.

Finally, Fig. 6 depicts the CDF of the user goodputs for UMTS LTE ($*$) and the theoretical capacity achieving systems with one ($\Box$), two ($\times$), and four ($\circ$) transmit and receive antennas, considering 20 UEs and assuming ideal IC, $f_0 = 0.8\,\mathrm{GHz}$ and $\Delta f = 20\,\mathrm{MHz}$ in UMi (solid lines) and RMa (dashed lines) environments.

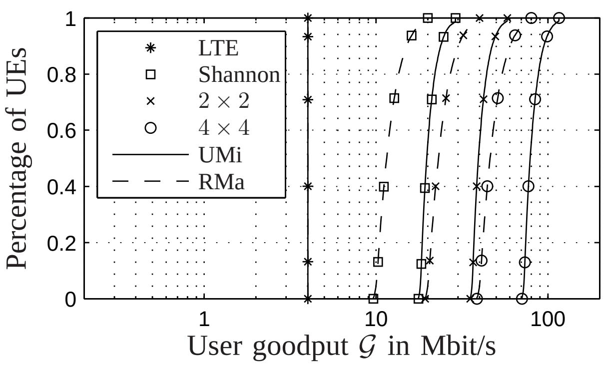


Fig. 6. CDF of user goodput $\mathcal{G}$: UMTS LTE and ideal capacity achieving systems, ideal IC, $f_0 = 0.8\,\mathrm{GHz}$, $\Delta f = 20\,\mathrm{MHz}$, 20 users.

The congruent vertical lines for UMTS LTE indicate that all users achieve the same maximum goodput of $\mathcal{G} = 4\,\mathrm{Mbit/s}$ in both considered environments. The potential gain from the combination of IC with MIMO techniques is obvious: IC does not only enable higher user goodputs due to the improved channel qualities, e.g., $\mathcal{G} > 100\,\mathrm{Mbit/s}$ for 4×4 MIMO in UMi environments. It also leads to a smaller difference between user goodputs at the cell edge and near the BS. The ratio between highest and lowest goodputs within a radio cell is decreased from more than 20 for systems without IC to approximately 2 in case of RMa environments and to approximately 1.5 in case of UMi environments if ideal IC is assumed.

6. Conclusions

In conclusion it can be stated that mobile broadband access is an option for sparsely populated rural areas if carrier frequencies with advantageous propagation characteristics are available as well as sufficient frequency bandwidth. Emerging technologies like MIMO and intelligent interference management will further improve the performance of future mobile broadband access networks at the price of increasing complexity and energy consumption. However, given the demand for increasing data rates observed for evolving applications and services, mobile broadband access is likely to stay a supplement to wired broadband access rather than becoming a full substitute. A noticeable difference between high-rate services for wired broadband access (e.g., high definition media) and lower-rate mobile data services (e.g., media streams fitted for handheld devices) is likely to remain over the next decade.

References

[1] F. Apel-Soetebeer and J. Rentmeister, *Breitbandatlas 2009_01 – Zentrale Ergebnisse, Teil I des Berichts zum Atlas für Breitband-Internet des BMWi*, Bundesministerium für Wirtschaft und Technologie (BMWi), June 2009, in German.

[2] F. Büllingen and P. Stamm, “Potenziale alternativer Techniken zur bedarfsgerechten Versorgung mit Breitbandzugängen,” wik-Consult, Projekt Nr. 22/05, wik-Consult Endbericht für das Bundesministerium für Wirtschaft und Technologie, Jan. 2006, in German.

[3] 3rd Generation Partnership Project (3GPP); Technical Specification Group Radio Access Network, “Evolved Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation,” TS 36.211, Version 8.2.0, Rel. 8, Mar. 2008.

[4] 3rd Generation Partnership Project (3GPP); Technical Specification Group Radio Access Network, “Evolved Terrestrial Radio Access (E-UTRA); Multiplexing and Channel Coding,” TS 36.212, Version 8.2.0, Rel. 8, Mar. 2008.

[5] 3rd Generation Partnership Project (3GPP); Technical Specification Group Radio Access Network, “Evolved Terrestrial Radio Access (E-UTRA); Radio Frequency (RF) system scenarios;,” TR 36.942, Version 8.2.0, Rel. 8, May 2009.

[6] 3rd Generation Partnership Project (3GPP); Technical Specification Group Radio Access Network, “Deployment aspects,” TR 25.943, Version 8.0.0, Rel. 8, Dec. 2008.

[7] European Co-operation in the Field of Scientific and Technical Research (COST) Action 231, “Digital Mobile Radio Towards Future Generation Systems,” Final Report, 1996.

[8] A. Rao, A. Weber, S. Gollamudi, and R. Soni, “LTE and HSPA+: Revolutionary and evolutionary solutions for global mobile broadband,” *Bell Lab. Tech. J.*, vol. 13, no. 4, pp. 7–34, 2009.

[9] E. Telatar, “Capacity of Multi-antenna Gaussian Channels,” *European Transactions on Telecommunications*, vol. 10, pp. 585–595, Nov. 1999.