Spectral Efficiency Assessment and Radio Performance Comparison between LTE and WiMAX

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Abstract— **This paper provides a detailed performance comparison between both upcoming OFDM based mobile technologies for broadband radio access – 3GPP UTRA LTE and mobile WiMAX (IEEE 802.16e). Based on link level simulation results, key performance indicators like physical layer throughput have been evaluated for different channel conditions and different modulation and coding schemes (MCS). Besides SISO, both MIMO 2x2 diversity and MIMO 2x2 spatial multiplexing scenarios have been investigated showing very promising results for the downlink direction. A thorough analysis has been presented highlighting the differences of both competing technologies and their impacts on spectral efficiency and radio performance. For this, in a first assessment, system parameters have been aligned towards equal peak throughput per MCS to show the technology specific behavior under different SNIR conditions. In a second assessment, full 3GPP and IEEE standard compliant system configurations have been ranked including for example typical layer one overhead. It has been shown that WiMAX as well as LTE prove to be state of the art technologies, with excellent performance but with certain advantages and disadvantages on both sides. The overall radio performance, however, is rather equal, thus clear-cut performance statements have to be based on higher layer design and even on network level.**

Keywords — E-UTRA, LTE, WiMAX, SNIR, AMC, MIMO, diversity, spatial multiplexing

I. INTRODUCTION

Mobile broadband access providing outstanding user data rates at lowest latencies gets reality within the next couple of years by the widespread deployment of OFDM based wireless technologies such as WiMAX and UTRA LTE [1] – [4]. The peak data rate will exceed 150 Mbps in 20 MHz bandwidth assuming moderate 2x2 MIMO. The end-to-end ping delays of roughly 10-20 ms will be achieved thanks to a flat IP based radio access network (RAN) architecture. The latter will consist of 2 nodes only, i.e. base stations called eNodeBs in LTE and APs in WiMAX as well as access gateways (aGWs) to the Internet.

Both technologies will offer wireless access as an alternative to fixed access, e.g. DSL like high data rate Internet services, and will even extend broadband services with mobility to areas where currently no fixed broadband access is feasible due to excessive costs on the last mile. Thanks to the extraordinary low delay in the order of a couple of milliseconds, enriched user experience with real time and interactive services will be achieved. Today's dominating circuit switched voice service will be substituted exclusively by packet based VoIP, which takes benefit from full multiplexing gain on shared radio resources.

Due to the fully data optimized architecture, significant improvements in spectral efficiency and data performance are expected. Both LTE and WiMAX utilize latest technology trends such as:

- deployments in tight frequency reuse, typically reuse 1
- flexible bandwidth scalability ranging from 1.25 / 1.4 MHz up to 20 MHz to ease refarming scenarios,
- orthogonal frequency division multiple access (OFDMA) [5] even partly combined with CDM components,
- flexible cyclic prefix (CP) configuration to combat excessive multipath e.g. for Broadcast service or hilly terrain environment,
- state-of-the-art Turbo Coding [6]-[7] with fast adaptive modulation and coding (AMC),
- Hybrid ARQ with Incremental Redundancy,
- adaptive MIMO with up to 4 antennas on receive and transmit side supporting both single-user as well as multi-user MIMO,
- various MIMO diversity and spatial multiplexing modes with dynamic switching depending on radio conditions [8]-[10],
- user specific Link Adaptation (AMC and Power Control) on signaling channels,
- short Time Transmission Intervals (TTIs) in the order of 1-2 ms to reduce latency and ping,
- sub-channeling with either localized allocations suitable for frequency selective packet scheduling or distributed allocations (for example with subcarrier permutation) aiming towards interference averaging and frequency diversity and
- persistent scheduling for high capacity VoIP use cases.

In this study WiMAX and LTE are analyzed from a physical layer perspective with focus on the dominant

978-1-4244-2644-7/08/$25.00

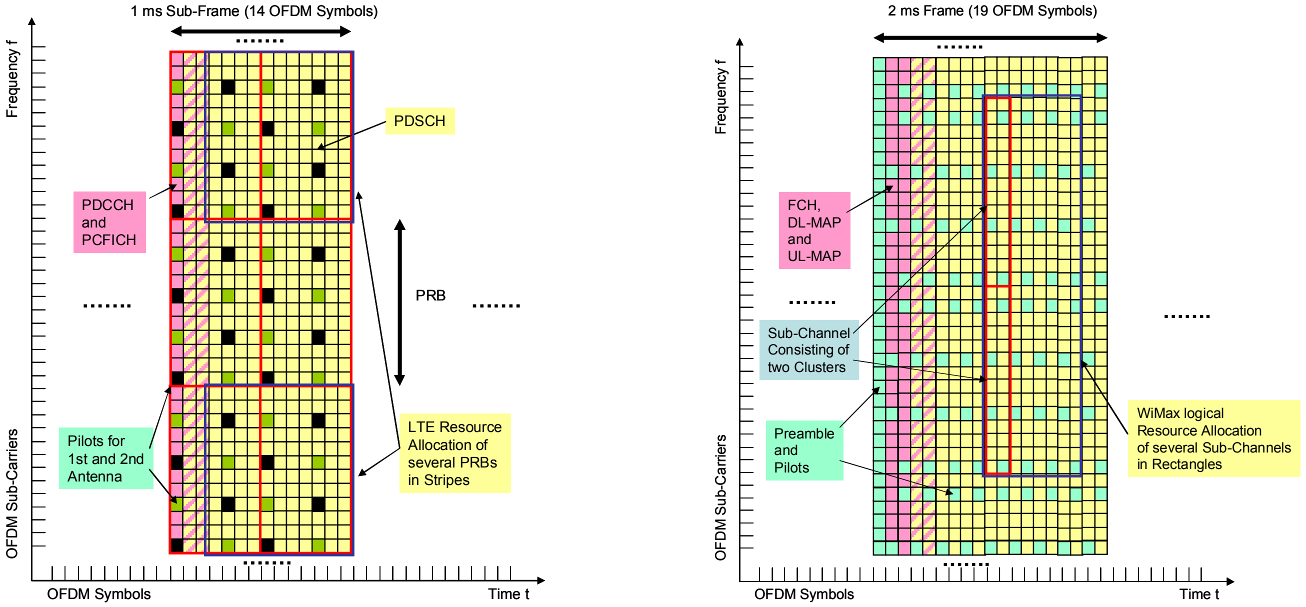

Fig. 1. Physical layer structure, overhead and user allocation for a) LTE on the left and b) WiMAX on the right hand side.

downlink direction. A comprehensive comparison of the physical layer performance in terms of user throughput under varying channel conditions will be presented by means of link level simulations. SISO, open loop MIMO diversity and MIMO spatial multiplexing scenarios are investigated up to a reasonable limit of 2x2 antennas suitable for initial field deployments. Especially physical layer characteristics like downlink frame format, pilot/preamble allocation, pilot power boosting, sub-channeling, coding and interleaving, and control channel allocation are accurately modeled. In contrast higher layer efficiency such as e.g. RLC/MAC overhead as well as effects on the system and network level have not been taken into account. A decent receiver performance based on real pilot based channel estimation (ML algorithm) has been assumed.

The paper is structured as follows. In Section II a brief overview regarding LTE and WiMAX air interface is presented comprising the most important differences of both technologies especially in the physical layer. A description of the link level simulation model is provided in Section III. Furthermore, all relevant simulation assumptions are introduced those which are applicable for both technologies, and those being different. The link level simulation results covering SISO, MIMO diversity and MIMO spatial multiplexing scenarios are shown in Section IV. The simulation results are discussed in detail, and explanations for the different behavior of WiMAX and LTE under certain conditions are derived. Finally, the main conclusions are drawn in Section V.

II. WIMAX AND LTE PHYSICAL LAYER DESIGN OVERVIEW

Both WiMAX and LTE rely on OFDM technology, but indeed the physical layer, to a certain extent, has been differently organized. Fig. 1 represents this for the downlink direction of LTE on the left, and of WiMAX on the right. For the downlink direction the most important performance relevant differences are listed in the following assuming 20 MHz bandwidth.

A. Frame Structure

WiMAX has configurable frame duration (2 ms – 20 ms) and typically 2 ms shall be assumed. This frame duration is not a multiple of the OFDM symbol length, so time padding shall be applied. In contrast the LTE frame with constant 10 ms length is partitioned into sub-frames of 1 ms TTI duration.

B. Sub-carrier Structure

Sub-carrier spacing at LTE is always kept fixed with 15 kHz, whereas in WiMAX the sub-carrier spacing depends on the selected bandwidth, e.g. 10.94 kHz for the selected 20 MHz bandwidth. In the same bandwidth LTE utilizes in total 1201 sub-carriers requiring 1201*15 kHz = 18.015 MHz leading to a guard band of 1.985 MHz. WiMAX occupies 1681 sub-carriers in 20 MHz resulting in 18.39 MHz and a guard of 1.61 MHz.

C. Cyclic Prefix Overhead

LTE offers the limited choice between two alternatives, short and long CP, with 4.6 µs and 16.7 µs, respectively. With a given useful symbol duration of 67 µs the CP overhead is given for short CP by ~7%. This yields to 14 OFDM symbols of 71.4 µs within a single 1 ms sub-frame. In contrast WiMAX proposes variable CP lengths of 1/32, 1/16, 1/8 and 1/4 of the useful symbol duration. Assuming CP = 1/16, an overhead of 6.25% has been obtained. With a useful symbol period of 91.4 µs and 5.7 µs CP, the entire symbol duration slightly exceeds 97 µs. This leads to 19 useful OFDM symbols per 2 ms frame.

D. Preamble and Pilot Overhead

LTE uses a rather sparse and optimized reference symbol allocation, which depends on the number of configured antennas and adds to a typical overhead of ~4.8% assuming SISO and ~9.5% assuming 2 x 2 MIMO. A preamble has not been foreseen in LTE. There are instead, primary and secondary synchronization sequences used. Both, called P-SynCH and S-SynCH, shall be repeated once in a 10 ms radio

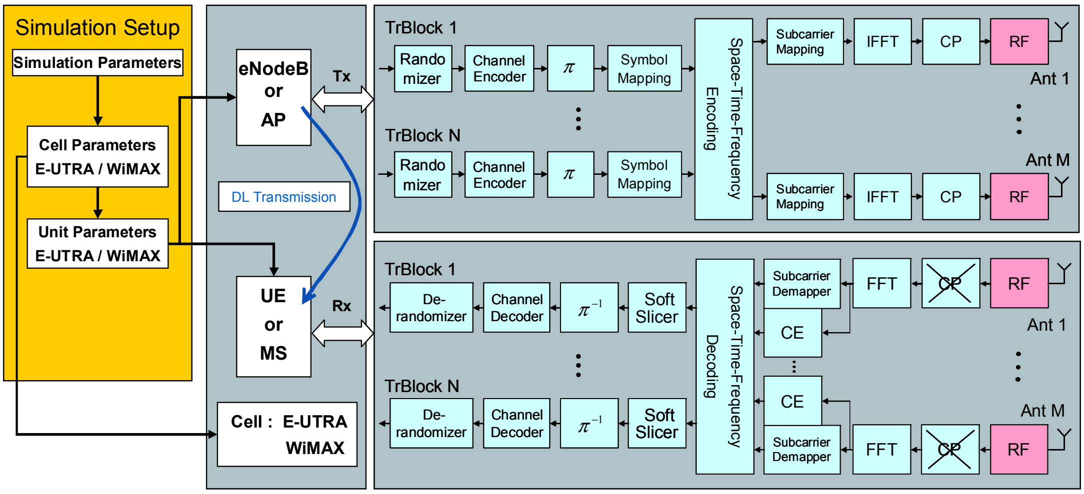

Fig. 2. 4GMAX link level simulator chain for the downlink direction including both transmit (Tx) and receive (Rx) units.

frame according to [2]. WiMAX DL frame starts with a preamble used for synchronization, covering a whole OFDM symbol thus occupying at least 5% of the frame. When *partial usage of sub-channels* (PUSC) is used, another 4 pilots are allocated per cluster of size 14 sub-carriers x 2 OFDM symbols. Hence, the total pilot overhead requires roughly 14.3% of all available sub-carriers for PUSC.

E. Downlink Control Channel Overhead

Physical Downlink Control Channel (PDCCH) in LTE consumes the first up to 3 OFDM symbols per sub-frame consisting of 14 OFDM symbols in total (assuming short CP). So the control overhead varies between 7% and 21% depending on the number of scheduled users per TTI. WiMAX submits scheduling and control information via the dynamic FCH/MAP region also located in the beginning of each frame. A minimum of 2 OFDM symbols is required for FCH/MAP, which are roughly 10.5% of the total frame.

F. Sub-channeling / Physical Resource Blocks

WiMAX in PUSC mode is based on sub-channels occupying two PUSC clusters with 28 subcarriers x 2 OFDM symbols. In 20 MHz bandwidth 60 sub-channels are available. The sub-channels are preferably mapped to sub-carriers via a permutation function for interference averaging purposes. Within a frame, sub-channels can be flexibly assigned to users in the two dimensional time frequency domain such that a rectangular user allocation has been obtained.

LTE partitions the 1 ms sub-frame into 12 x 14 stripes, which are called Physical Resource Blocks (PRBs) The mapping of LTE PRBs on physical sub-carriers is either localized or distributed with the first one as preferred mode to allow for efficient frequency selective packet scheduling.

III. SIMULATION MODEL AND SIMULATION ASSUMPTIONS

A. 4GMAX Link Level Simulator Environment

At Nokia Siemens Networks a common link level simulator for OFDM system was developed, called 4GMAX. It provides a platform for both WiMAX and LTE. An overview of the 4GMAX simulation chain has been presented in Fig. 2. The radio access technology (RAT) to be used is defined by specific simulation settings and each transmit (Tx) and receive (Rx) unit is configured appropriately. The overall structure of the link level simulator has been defined generally enough such that the two RATs under study exclusively differ in the specific algorithms used in the different modules of the simulator (e.g. bit and symbol processing, modulation, etc.). In this way, additional side effects from using different simulation platforms for WiMAX and LTE are avoided which is a basic and fundamental prerequisite for a fair RAT performance comparison.

B. General Simulation Assumptions and Parameters

In Table I the essential simulation assumptions and parameters are listed, which are applied to the LTE/E-UTRA vs. WiMAX performance comparison study. Focus is set on scenarios in the 2.6 GHz band with 20 MHz bandwidth. Slow

TABLE I. ESSENTIAL LINK LEVEL SIMULATION PARAMETERS APPLICABLE FOR BOTH WIMAX AND LTE

	Parameter Type	E-UTRA	WiMAX
Common	*Frequency Band*	*2.6 GHz*	
	System Bandwidth	*20 MHz*	
	FFT Size	*2048*	
	Duplex Mode	*FDD*	
	Transmit Direction	*DL*	
	Simulation Time	*1 s, 5 s*	
	Channel Coding	*CTCU (Rc=1/2, 2/3, 3/4)*	
	Modulation Format	*4-QAM, 16-QAM, 64-QAM*	
	Channel Type	*PedA 3 km/h, VehA 30 km/h according to UMTS 30.03*	
	Channel Estimation	*Frequency Domain Maximum Likelihood*	
	Receiver Type	*MMSE*	
	Tx-Rx Antennas	*1 x 1, 2 x 2*	
RAT-specific	*Frame Period*	*10 ms*	*2 ms*
	Subframe Length / TTI	*1 ms*	*2 ms*
	Subcarrier Spacing	*15 kHz*	*10.94 kHz*
	Cyclic Prefix	*Short CP*	*1/16*
	Code Block Length	*1 ms*	*MCS-based (see Table III)*
	TX Diversity	*Space-Frequency Coding*	*Space-Time Coding*
	Pilot Power Boosting	*No*	*Off (mandatory feature)*
	Subcarrier Permutation	*No*	*Mandatory*

moving terminals as well as those with medium velocity are assumed (PedA and VehA propagation models due to [11], [12]). Spatial channel correlation is neglected, assuming sufficient antenna elements separation and wide angular spread. The simulation parameters are split into two major groups, first the common parameters applicable for both technologies and second the RAT-specific ones. Though both RATs are based on scalable OFDMA principle, there are some significant differences clearly visible. In order to provide a fair comparison, features which are only optional in one standard, but mandatory in the other have been highlighted. A particular example is the fact that the IEEE 802.16 WiMAX standard as well as 3GPP LTE support both frequency division duplex (FDD) and time division duplex (TDD) modes of operation. In practical applications, however, WiMAX is mostly a TDD-based system whereas LTE dominantly utilizes FDD. In this study the frequency division duplex mode according to LTE has been selected, since nowadays FDD seems to be the preferred solution of incumbent access network operators due to higher availability of FDD spectrum. Another alignment has been done in terms of channel coding. For both systems Convolutional Turbo Codes including the internal interleaver from UMTS (CTCU) have been applied. Nevertheless, different transport block sizes are signaled from higher layers: LTE has a sub-frame based transport block, whereas WiMAX operates at much shorter code block size, which is based on concatenation of sub-channels depending on the chosen MCS. Finally a unified maximum likelihood algorithm has been used for real channel estimation in both technologies, which relies on FFT in frequency domain and on initial estimates in time direction [13]. However, for simplification the channel power delay profile is assumed to be perfectly known.

Note that pilot power boosting has so far only been assumed for WiMAX despite of the ongoing LTE standard initiative regarding that issue. For comparison reasons simulation results have been performed with WiMAX pilot power boosting being switched off.

C. *RAT specific Simulation Assumptions*

In Table II overhead values for both technologies have been compared assuming 20 MHz bandwidth for network deployment. Signaling efficiency in terms of load dependent downlink control channel capacity (MAP for WiMAX and PDCCH for LTE) has not been considered, since only a single UE always occupying the whole bandwidth has been taken into account in the link level study. Time padding for WiMAX produces substantial overhead due to missing alignment of frame and OFDM symbol durations. It is worth to mention that, in case of LTE, the number of pilots scales with the number of transmit antennas. In contrast the WiMAX pilot overhead is independent of the number of transmit antennas and constant but nevertheless much higher than that in LTE. The following simulation results will confirm the overhead differences consequently resulting in significantly different MCS dependent peak throughput rates.

TABLE II. TECHNOLOGY SPECIFIC OVERHEAD VALUES FOR BOTH WIMAX AND LTE

Overhead Type	E-UTRA	WiMAX
Pilot Overhead (1x1), (2x2)	*4.76 % resp. 9.52 %*	*14.3 %*
Preamble/SynCH Overhead	*0.14 %*	*4.8 %*
MAP / PDCCH Overhead / Padding	*no / no / no*	*no / no / 7.7%*
CP Overhead	*7.03 %*	*6.25 %*
Guard Bands	*1.985 MHz*	*1.61 MHz*

To eliminate the influence of different RAT specific overhead and to concentrate on the pure radio performance for both systems appropriate simulation settings have been introduced, which deliver the *same maximal data rate per MCS*. For instance, when SISO transmission mode is assumed, in LTE 6 PRBs (out of 100 within 1 ms) have been assigned to one user while in WiMAX 40 PRBs (out of 540 within 2 ms) have been allocated. Both lead to a bit rate of 960 kbit/s. Dependent on the modulation and coding scheme different user data rates are obtained as shown in Table III.

TABLE III. CALCULATION OF RESOURCES NEEDED TO OBTAIN THE SAME PEAK DATA RATE PER MCS IN BOTH LTE AND WIMAX

Antenna Configuration	Radio Access Technology	Subframe Lenght (ms)	Number PRBs / Subframe	MCS	Codeblock Concatenation Number PRBs / Codeblock	Number info bits	Bit Rate (kbit/s)
SISO	WiMAX (48 data carriers)	2	40	QPSK, Rc = 1/2	10	1920	960
				QPSK, Rc = 3/4	6	2880	1440
				16-QAM, Rc = 1/2	5	3840	1920
				16-QAM, Rc = 3/4	3	5760	2880
				64-QAM, Rc = 2/3	2	7680	3840
	E-UTRA (160 data carriers)	1	6	QPSK, Rc = 1/2	6	960	960
				QPSK, Rc = 3/4		1440	1440
				16-QAM, Rc = 1/2		1920	1920
				16-QAM, Rc = 3/4		2880	2880
				64-QAM, Rc = 2/3		3840	3840
MIMO (2 x 2) TxDiv MRC	WiMAX (48 data carriers)	2	38	QPSK, Rc = 1/2	10	1824	912
				QPSK, Rc = 3/4	6	2736	1368
				16-QAM, Rc = 1/2	5	3648	1824
				16-QAM, Rc = 3/4	3	5472	2736
				64-QAM, Rc = 2/3	2	7296	3648
	E-UTRA (152 data carriers)	1	6	QPSK, Rc = 1/2	6	912	912
				QPSK, Rc = 3/4		1368	1368
				16-QAM, Rc = 1/2		1824	1824
				16-QAM, Rc = 3/4		2736	2736
				64-QAM, Rc = 2/3		3648	3648
MIMO (2 x 2) SpMux MMSE	WiMAX (48 data carriers)	2	38	QPSK, Rc = 1/2	10	2 x 1824	1824
				QPSK, Rc = 3/4	6	2 x 2736	2736
				16-QAM, Rc = 1/2	5	2 x 3648	3648
				16-QAM, Rc = 3/4	3	2 x 5472	5472
				64-QAM, Rc = 2/3	2	2 x 7296	7296
	E-UTRA (152 data carriers)	1	6	QPSK, Rc = 1/2	6	2 x 912	1824
				QPSK, Rc = 3/4		2 x 1368	2736
				16-QAM, Rc = 1/2		2 x 1824	3648
				16-QAM, Rc = 3/4		2 x 2736	5472
				64-QAM, Rc = 2/3		2 x 3648	7296

The reason for such an alignment is the fact that terminals in both systems will concurrently request for resources. In a real load scenario it is very likely that only a fraction of the total bandwidth is available per user.

IV. SIMULATION RESULTS

A. *SISO*

Fig.3 shows the throughput vs. SNIR curves for several selected MCS in the VehA 30 km/h single antenna scenario applying the settings from Table III.

Recall that according to these settings the maximum throughput is limited to 3.84 Mbps for the 64-QAM 2/3 scheme, since only 6% of the available resources have been utilized (corresponds to roughly 1 MHz bandwidth). For full bandwidth occupation of 20 MHz, data rates of roughly 64 Mbps would have been expected. Obviously the performance of WiMAX and LTE proves to be nearly identical; no significant differences are visible over the entire SNIR range. It is important to note, that ideal adaptive modulation and coding (AMC) based on optimum switching points will provide the throughput envelope over all MCS. In this case MCS 2, i.e. 4-QAM Rc=3/4, obviously becomes obsolete, since it is completely outperformed by 16-QAM Rc=1/2. However, another criterion, which should be considered for the definition of the SNIR regions per MCS, is the Block Error Rate (BLER). Assuming a first transmission target BLER of e.g. 10% and

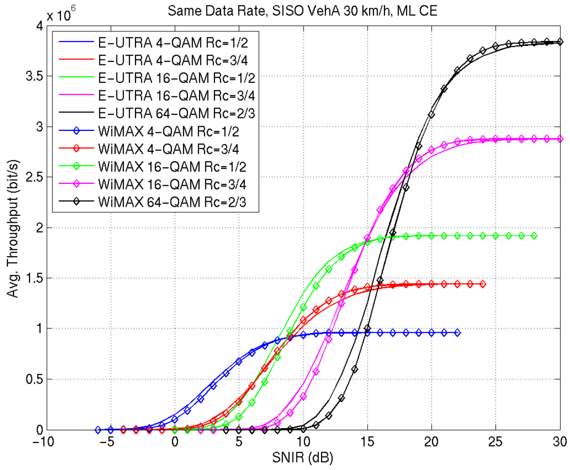

Fig. 3. Average throughput in case of SISO for VehA 30 km/h (zero spatial correlation) and ML channel estimation algorithm (equal peak throughput settings equivalent to 1 MHz bandwidth).

subsequent application of fast Hybrid ARQ will result in a desired residual BLER < 10^{-2} and hence will ensure the required service quality.

B. *MIMO 2x2 Diversity*

Fig. 4 shows the corresponding throughput vs. SNIR results for the MIMO 2 x 2 diversity scenario assuming equal peak throughput settings according to Table III. In downlink diversity is an open loop Alamouti based SFBC (in LTE) and STBC (in WiMAX) [10]. As expected overall a clear diversity gain of roughly 5 dB gets visible with respect to the SISO simulation results in Fig. 3.

In case of 4-QAM Rc = 3/4 WiMAX and LTE provide equal performance results. For all other MCS LTE reveals a small but negligible gain of maximum 1 dB.

Taking into account the RAT-specific overhead and applying full 20 MHz allocation of resources, the situation looks slightly different. Fig. 5 depicts the maximum achievable capacity for 20 MHz bandwidth in case of PedA channel and 3 km/h mobility (slow moving subscribers). LTE has considerably less overhead than WiMAX thus providing roughly 17% higher throughput for every individual MCS at high SNIR. For example assuming 64-QAM Rc=2/3 LTE obtains 60.8 Mbps whereas WiMAX achieves only 51.84 Mbps for SNIR exceeding 15 dB. Furthermore assuming an ideal AMC the throughput envelope of LTE shows approximately 2.5 dB gain compared to that of WiMAX. Note that according to Table I WiMAX pilot power boost of 2.5 dB has been omitted, which might compensate or at least shrink this gap to a certain extent.

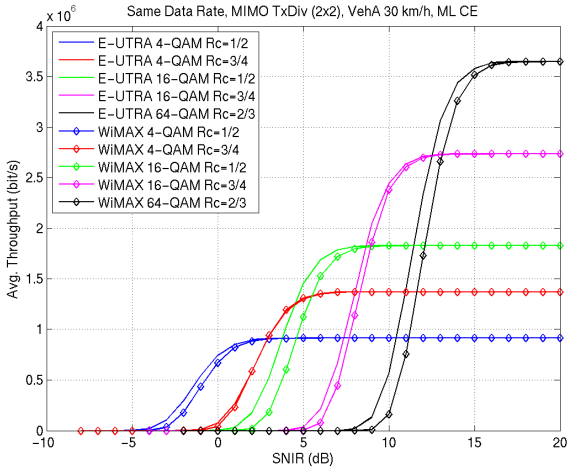

Fig. 4. Average throughput for MIMO 2x2 Diversity, spatially uncorrelated VehA 30 km/h and ML channel estimation (equal peak throughput settings).

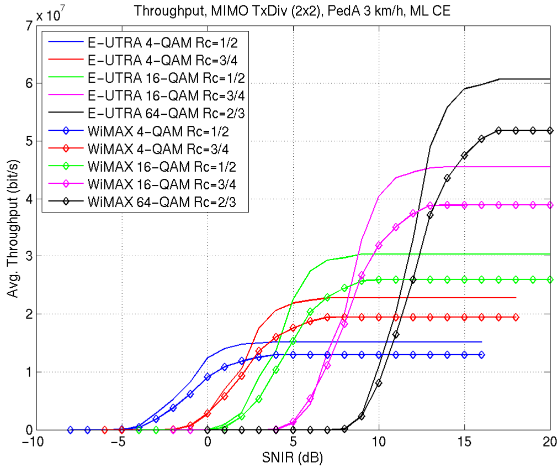

Fig. 5. Average throughput in case of MIMO 2x2 Diversity for PedA 3 km/h (zero spatial correlation) and ML channel estimation algorithm for 20 MHz bandwidth (including all overhead).

C. *MIMO 2x2 Spatial Multiplexing*

Fig. 6 shows results for normalized data rate when open loop MIMO spatial multiplexing for 2 Tx and 2 Rx antennas has been applied. WiMAX offers the possibility to switch between *horizontal encoding* (HE) and *vertical encoding* (VE). In the first case two streams of information bits are encoded and interleaved independently. The same double stream

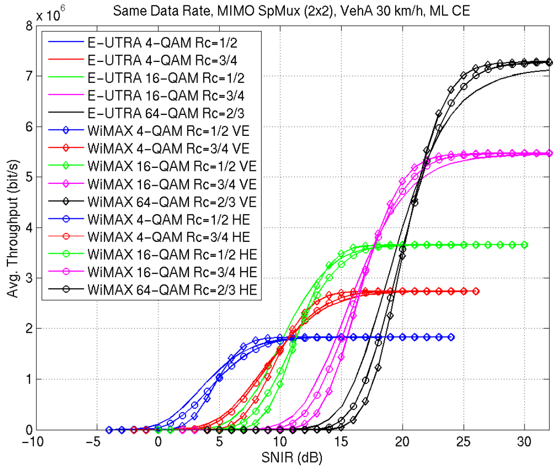

Fig. 6. Average throughput in case of MIMO 2x2 Spatial Multiplexing for spatially uncorrelated VehA 30 km/h and ML channel estimation algorithm (equal peak throughput settings).

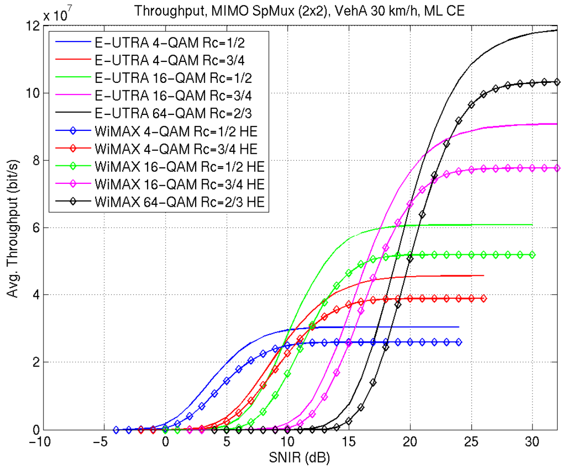

Fig. 7. Average throughput for 20 MHz bandwidth in case of MIMO 2x2 Spatial Multiplexing for spatially uncorrelated PedA 3 km/h and ML channel estimation algorithm (incl. all overhead).

method has also been applied to LTE. In the second case a single stream of information bits is encoded and interleaved first and thereafter a separation of this output in two spatial streams has been provided. Similar to SISO and MIMO diversity the performance of both RATs is nearly equal with slight but negligible advantages in the order of 1 dB in favor of LTE.

MIMO spatial multiplexing results in a SNIR degradation of roughly 5 dB compared to MIMO diversity (cf. Fig. 6 and Fig. 4). In contrast to SISO, however, MIMO spatial multiplexing allows for almost doubling the throughput for a certain MCS at high SNIR (cf. Fig. 6 and Fig. 3).

Fig. 7 shows throughput results for MIMO 2x2 spatial multiplexing assuming 20 MHz bandwidth when all available resources have been allocated to a single user. All relevant overhead has been taken into account. For example assuming 64-QAM Rc=2/3 LTE obtains 121.6 Mbps whereas WiMAX achieves only 103.7 Mbps for SNIR exceeding 25 dB. LTE again shows a moderate SINR gain of about 1.5 dB as well as the higher peak throughput for each individual MCS according to the lower overhead.

D. *Dynamic Adaptive MIMO Switch*

Fig. 8 depicts the optimum dynamic MIMO switching area between open loop diversity and spatial multiplexing for both RATs. It is located around the coincidence between the throughput envelopes. Apparently for open loop MIMO both LTE as well as WiMAX have an optimum switching SNIR value of roughly 18 dB. The accuracy of this value is mostly affected by changing spatial correlation in a real propagation environment.

V. CONCLUSIONS

In this paper a profound comparison of UTRA LTE and WiMAX has been presented with focus on radio interface performance. Although both competing 4G technologies provide a comprehensive state-of-the-art feature content differences in the air interface design lead to characteristic effects, which have been thoroughly evaluated and explained. Nevertheless the overall radio performance is rather equal with LTE slightly outperforming WiMAX due to the lower overhead. Higher layer effects such as RLC/MAC and signaling overhead have not been considered, which might lead to additional impacts on the overall network performance.

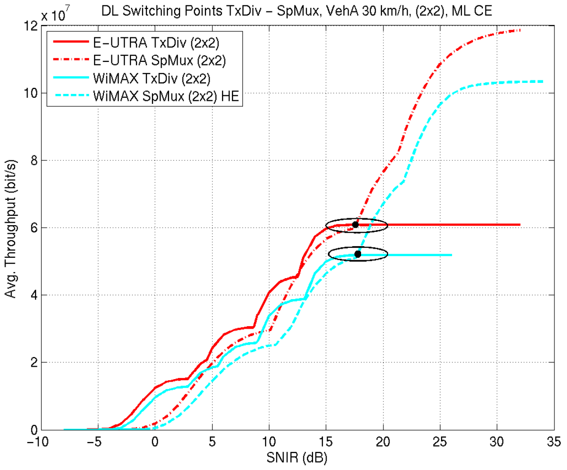

Fig. 8. Optimum dynamic MIMO switch defined by the throughput envelopes for MIMO spatial multiplexing and MIMO diversity; 20 MHz bandwidth, spatially uncorrelated VehA 30 km/h and ML channel estimation algorithm (including all overhead) assumed.

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