# Upper Bound Cell Spectral Efficiency of IMT-Advanced Scenarios

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***Abstract*—The International Telecommunication Union - Radio Group (ITU-R) has established a set of requirements to be met by candidate systems to be accepted as International Mobile Telecommunications - Advanced (IMT-A) compliant and has set up evaluation guidelines to asses compliance. In this paper, a numerical model following these guidelines is introduced to determine the upper bound cell spectral efficiency of Orthogonal Frequency Division Multiple Access (OFDMA) systems. In the model rate fair scheduling of concurrent Mobile Stations (MSs) and constant transmit power is assumed. The numerical results when compared to the IMT-A requirements show that the requirements can be met in general only by using Multiple Input Multiple Output (MIMO) transmission and a high degree of coordination between adjacent cells.**

## I. Introduction

Mobile Internet applications are becoming more and more popular and require considerably higher data rate of mobile radio networks than ever. To meet increasing capacity demands new mobile radio network standards, such as IEEE 802.16m [1] and Long-Term Evolution - Advanced (LTE-A) [2] are currently under development. These new standards fulfill the minimum requirements set up by the ITU-R to be IMT-A compliant [3]. The IMT-A requirements shall guarantee that the proposed system standards will meet the increasing capacity demands. Only compliant systems will be allowed to operate in the frequency spectrum assigned by ITU-R for use by future high rate mobile radio networks.

One important IMT-A requirement addresses cell spectral efficiency as a main indicator for the capacity a mobile radio network can provide. The spectral efficiency evaluated for IMT-A systems in [4], [5] was found from system level simulation, only. In this paper, a system model is presented and evaluated to numerically calculate the upper bound cell spectral efficiency for some IMT-A scenarios. The system is assumed to operate in Time Division Duplex (TDD) mode. So far, comparable system models have been used only to evaluate wireless mesh networks [6], [7].

In Chapter II the system model is introduced, in Chapter III the evaluated scenarios are described, in Chapter IV we present our results and end with conclusions in Chapter V.

## II. System Model

The system model comprises three independent models, the IMT-A channel model, the Physical Layer (PHY) model and the Media Access Control (MAC) layer model.

### A. IMT-A Channel Model

According to [8] the IMT-A channel model provides methods to calculate the components contributing to the attenuation $\mathrm{Att}$ of a transmission from station $S_i$ to $S_j$, located at positions $p_i$ and $p_j$, respectively. The components considered in this work are path loss $\mathrm{PL}$, transmit antenna gain $G_{TX}$, receive antenna gain $G_{RX}$ and shadowing $X_{SHA}$. Fast-fading is not modeled.

$$\mathrm{Att}[dB] = \mathrm{PL} - G_{TX} - G_{RX} + X_{SHA} \tag{1}$$

*a) Path Loss:* Radio links are categorized into two types according to their propagation characteristics: For Line-of-Sight (LOS) links the direct path between $S_i$ and $S_j$ dominates the indirect paths resulting from reflections, scattering and diffraction. Thus, the self interference of the signal is limited resulting in only moderate path loss $\mathrm{PL}_{LOS}$ over distance. In contrast, for Non-Line-of-Sight (NLOS) links there is no dominating direct path and the self interference results in heavy path loss $\mathrm{PL}_{NLOS}$ over distance.

Both types of links are represented in the IMT-A channel model. For each discrete scenario instance, the decision if the link between a pair of stations is LOS or NLOS is determined once. The decision is assumed time invariant and valid for both transmission directions. It is made based on a random variable $X$ uniformly distributed between zero and one. If an instance of $X$ does not exceed a certain threshold that depends on the distance $d$ between $S_i$ and $S_j$, the corresponding link is assumed to be LOS type. The threshold is specified by function $P_{LOS}(d)$ and decreases with increased distance. Thus, the outdoor path loss $\mathrm{PL}_{out}$ is expressed as:

$$\mathrm{PL}_{out}[dB] = \begin{cases} \mathrm{PL}_{LOS} & \text{if } x > P_{LOS}(d) \\ \mathrm{PL}_{NLOS} & \text{else} \end{cases} \tag{2}$$

For some IMT-A scenarios a certain probability is used for MSs to be located inside buildings or in vehicles. MSs inside buildings or in vehicles suffer from an additional path loss $\mathrm{PL}_{in}$. In some scenario type the additional path loss value is a constant $c$, in some other scenario types $\mathrm{PL}_{in}$ additionally depends on a log-normal distributed random variable $X_{SHA,2}$ that is drawn either once per MS and scenario instance ($X_{SHA,2}(p_i)$) or once per pair of MS and Base Station (BS) and scenario instance ($X_{SHA,2}(p_i, p_j)$). In the first case the additional path loss introduced by $X_{SHA,2}$ is equal for all links of a certain MS to different BSs. In the latter case $X_{SHA,2}$ is specific for each link of a certain MS connecting to different BSs. $\mathrm{PL}_{in}$ is time invariant and given by:

$$\mathrm{PL}_{in}[dB] = \begin{cases} 0 & \text{outside buildings/verhicles} \\ c & \text{inside buildings (suburban)} \\ c + X(p_i, p_j) & \text{inside buildings (urban)} \\ c + X(p_i) & \text{inside vehicles} \end{cases} \quad (3)$$

Thus, the overall path loss is:

$$\mathrm{PL}[dB] = \mathrm{PL}_{out} + \mathrm{PL}_{in} \quad (4)$$

*b) Antenna Gain:* For the MSs, the IMT-A channel model requires omni-directional antennas without any antenna gain. When using MIMO transmissions, up to two antennas may be co-located. The IMT-A channel model specifies sector antennas at BSs with a 3 dB beam width of 70° in the horizontal plane and 15° in the elevation direction. The maximum antenna gain in main beam direction is 17 dBi. Depending on the scenario the antenna down tilt is 6° or 12°. Up to four antennas may be co-located for MIMO transmissions.

*c) Shadowing:* All links suffer from spatially correlated shadowing due to obstacles as specified by a log-normal distribution. An instance of a random variable is determined once for each pair of stations and scenario instance. Hence, it is time invariant and valid for both transmission directions.

### B. Physical Layer Model

The PHY model decides under which conditions a transmission is successful, i.e. the transmitted data can be decoded error-free, and at what data rate can be transmitted. First, the Signal-to-Interference+Noise-Ratio (SINR) for each receiving station is calculated. In a second step, the MIMO gain is determined and the according $\mathrm{SINR}_{\mathrm{eff}}$ calculated. In the last step the $\mathrm{SINR}_{\mathrm{eff}}$ is mapped to a data rate. The data rate is then fed as input to the MAC layer model described in the following subsection.

Let $\{S_t : t \in T\}$ be the set of stations transmitting at a certain time instance and $P_t$ the transmit power of $S_t$. If station $S_j, j \notin T$ receives a transmission from station $S_t, t \in T$, the SINR at $S_j$ is (in linear domain):

$$\mathrm{SINR}(S_t, S_j, T) = \frac{P_t \cdot \mathrm{Att}(S_t, S_j)}{Noise + \sum_{m \in T, m \neq t} P_m \cdot \mathrm{Att}(S_m, S_j)} \quad (5)$$

The MIMO gain depends on the number of transmit $n_{tx}$ and receive antennas $n_{rx}$. In this work, ideal single-user MIMO is assumed to determine the upper bound cell spectral efficiency. Thus, the SINR of each station is mapped to an $\mathrm{SINR}_{\mathrm{eff}}$ according to [9]:

$$\mathrm{SINR}_{\mathrm{eff}}(S_t, S_j, T) = \mathrm{SINR}(S_t, S_j, T) + 10 \log_{10}\left(\frac{n_{rx} - n_{tx} + 1}{n_{tx}}\right) \quad (6)$$

The $\mathrm{SINR}_{\mathrm{eff}}$ is then mapped to a data rate using the Shannon theorem [10] enhanced by a factor $n_{stream} = n_{tx}$ representing the number of simultaneous spatial MIMO streams. Thus, the data rate $R$ for the signal bandwidth $B$ calculates to:

$$R(S_t, S_j, T) = n_{stream} \cdot B \cdot \mathrm{ld}(1 + \mathrm{SINR}_{\mathrm{eff}}(S_t, S_j, T)) \quad (7)$$

Clearly, this results in the maximum possible MIMO gain.

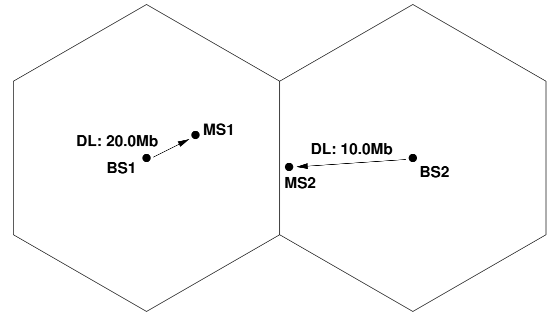


Fig. 1. Scenario with two BSs transmitting a fix amount of data to their associated MSs.

### C. Medium Access Control Model

The MAC model is concerned with coordination of the transmissions between BS and MSs on both, Up-Link (UL) and Down-Link (DL). As the wireless channel is a shared medium all transmissions mutually interfere each other. The MAC model coordinates subsets of transmissions, called Network States (NSs), in such a way that their mutual interference is limited while the overall throughput of the stations is maximized. All subsets together build the so called schedule.

The model is based on the capacity regions model introduced in [11]. Different from that model our model does not consider routing since one-hop connections occur in our model, only. The MAC model assumes an omniscient scheduling entity that has full knowledge of the interference conditions for each station in the scenario based on the PHY model. While building the subsets the model controls the traffic load for each transmission to meet end-to-end requirements set by the stations involved. The optimal schedule is assumed to be available at all stations without any transmission cost.

Consider the simple scenario shown in Figure 1: BS1 wants to transmit 20.0 Mb of data to MS1 and BS2 wants to transmit 10.0 Mb of data to MS2, both BSs using the same channel resource. Thus, there are three possible network states $\mathrm{NS}_i$:

1) $\mathrm{NS}_1$: BS1 transmits, BS2 does not transmit (Figure 2a)
2) $\mathrm{NS}_2$: BS1 does not transmit, BS2 transmits (Figure 2b)
3) $\mathrm{NS}_3$: BS1 and BS2 transmit simultaneously (Figure 2c)

When only a single BS transmits, the transmission data rate to its associated MS is higher than in case both BSs transmit owing to mutual interference. However, the sum data rate of the two transmissions is, in this example, higher in case of simultaneous transmissions. The task of the MAC model is to find the optimal duration $\delta_i$ for $\mathrm{NS}_i$ such that the duration of the schedule for all the consecutive NSs is minimized. The durations are written as vector $\delta^* = (\delta_1, ..., \delta_i)$. The NSs are


(a) $\mathrm{NS}_1$


(b) $\mathrm{NS}_2$


(c) $\mathrm{NS}_3$

Fig. 2. All possible network states for the scenario shown in Figure 1

written as vectors $\mathrm{NS}_i$ where the entries of the vectors are

$$ns[i] = \begin{cases} r & \text{if transmission } i \text{ is active at data rate r}\,^{\mathrm{Mb}}\!/\!_{\mathrm{s}} \\ 0 & \text{otherwise.} \end{cases} \tag{8}$$

Thus, the NS vectors for the example in Figure 1 are

$$\mathrm{NS}_1 = \begin{pmatrix} 15.0 \\ 0.0 \\ 0.0 \\ 0.0 \end{pmatrix}, \mathrm{NS}_2 = \begin{pmatrix} 0.0 \\ 5.0 \\ 0.0 \\ 0.0 \end{pmatrix}, \mathrm{NS}_3 = \begin{pmatrix} 10.0 \\ 2.5 \\ 0.0 \\ 0.0 \end{pmatrix}$$

where the entries represent, from top to bottom, the data rates of transmissions from BS1 to MS1, from BS2 to MS2, from MS1 to BS1 and from MS2 to BS2. As only DL traffic is considered in this example the third and fourth entries of each NS are zero.

The traffic demands of all stations can be combined to a single traffic vector $T$. The entries of the vector are

$$t[m] = \begin{cases} t & \text{if station } S_m \text{ wants to transmit t Mb of data} \\ 0 & \text{otherwise.} \end{cases} \tag{9}$$

Hence, vector $T$ for the example is

$$T = \begin{pmatrix} 20.0 \\ 10.0 \\ 0.0 \\ 0.0 \end{pmatrix}.$$

To find the optimal schedule a Linear Programming (LP) problem has to be solved:

$$\begin{aligned} & \textstyle\sum_i \delta_i \cdot \mathrm{NS}_i = T \\ \text{such that} \quad & \textstyle\sum_i \delta_i \text{ is minimal.} \end{aligned} \tag{10}$$

As already mentioned, the solution to the LP problem is the vector $\delta^* = (\delta_1, ..., \delta_i)$. In the example, the vector is $\delta^* = (0.0, 1.0, 2.0)$.

Hence, the duration of the schedule $D_{schedule}$ is:

$$D_{schedule} = \sum_i \delta_i \tag{11}$$

The total Traffic $T_{total}$ carried during $D_{schedule}$ is the sum of all entries $t_i$ of the traffic vector $T$:

$$T_{total} = \sum_i t_i \tag{12}$$

The system capacity is the carried traffic during the schedule duration:

$$C = \frac{T_{total}}{D_{schedule}}, \tag{13}$$

for the example scenario it is

$$C = \frac{20\,\mathrm{Mb} + 10\,\mathrm{Mb}}{1\,\mathrm{s} + 2\,\mathrm{s}} = 10\,^{\mathrm{Mb}}\!/\!_{\mathrm{s}}.$$

## III. Scenario Setup

The ITU-R guidelines [8] specify a set of test environments to be used in the evaluation process, namely "micro-cellular", "base coverage urban", "high speed" and other. For the three test environments mentioned several deployment scenarios are defined. In this paper, the deployment scenarios "Urban mirco-cell (UMi)" specified for the micro-cellular test environment, "Urban macro-cell (UMa)" and "Suburban macro-cell (SMa)" specified for the base coverage urban test environment and "Rural macro-cell (RMa)" specified for the high speed test environment are evaluated. All deployment scenarios have a regular cell structure with each BS serving three cells [1].

For realistic modeling of interference, at the edges of the scenarios a wrap-around technique is applied. Wrap-around means that the scenario is continued in all directions by copies thereof. Thus, there are six copies of the scenario distributed equally spaced around a sphere. All copied stations transmit at the same time as transmissions happen at the corresponding stations in the inner part of the scenario.

The complexity of the system model introduced in Section II increases exponentially with the number of stations. Hence, the number of stations is small for which the optimal schedule can be calculated in limited time duration.

In this paper, a wrap-around scenario with three instead of 19 BS sites, as specified by the ITU-R for IMT-A evaluation, has been chosen, see Figure 3. Furthermore, instead of 10 MSs per BS on average, as also specified by the ITU-R, only three MSs per BS are assumed and no power control is applied, since this would increase the complexity of the LP problem, too.

The three test environments differ in the Inter Site Distance (ISD), the shortest distance between two BS sites, and the deployment scenario used (Table I). All parameters comply to the requirements specified in [8].

Results presented in the next section are valid only with 100 % traffic going in the DL direction from BS to MS as it is expected that most traffic will go from the Internet to the user and thus the DL will limit the system capacity. Since in real systems there will be some UL traffic, too, the assumption of 100 % DL traffic will result in an upper bound system capacity. To assure statistical significance of the results

[1] In the context of IMT-A evaluation sectors are called cells.

TABLE I
TEST ENVIRONMENTS

| **Parameter** | **Micro-cellular** | **Base coverage urban** | **High speed** | **Base coverage urban (optional)** |
|---|---|---|---|---|
| Deployment scenario | Urban Micro (UMi) | Urban Macro (UMa) | Rural Macro (RMa) | Suburban Macro (SMa) |
| ISD | 200 m | 500 m | 1732 m | 1299 m |

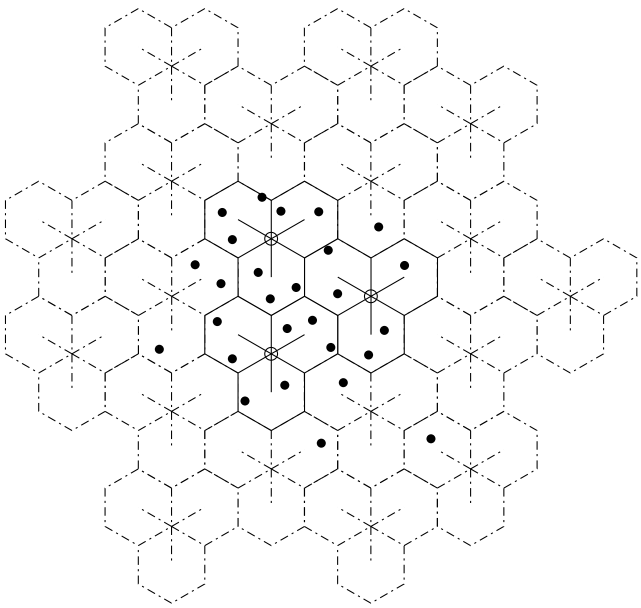

Fig. 3. Evaluated scenario showing the three coordinated BS sites (solid shaped) each serving three cells with MSs associated (dots) and the 18 corresponding wrap-around BS sites (dash-dotted shaped)

multiple drops of scenario instances have been generated and calculated where each drop stands for a different placement of uniformly distributed MSs.

In this work, the same traffic demand is to be served to each MS. Thus, the schedule calculated by solving the LP problem assures that all MSs get the same data rate and thus the schedule is rate fair. We feel that this is the most reasonable assumption w.r.t. fairness to MSs, independent of their location in the cell.

## IV. RESULTS

First, some validation results are introduced to proof the accuracy of the implemented IMT-A scenarios. Then, numerical results for the cell spectral efficiency are presented and compared against IMT-A requirements.

### A. Validation Results

The validation of the IMT-A scenarios considered not only covers the channel model but also the distribution of MSs within the respective scenarios, the association of MSs to BSs and the scenario geometry. Only if all these issues are correctly implemented, the resulting path loss Cumulative Distribution Function (CDF) and SINR CDF will match the CDFs taken as a reference from the WINNER+ IMT-A evaluation report [4].

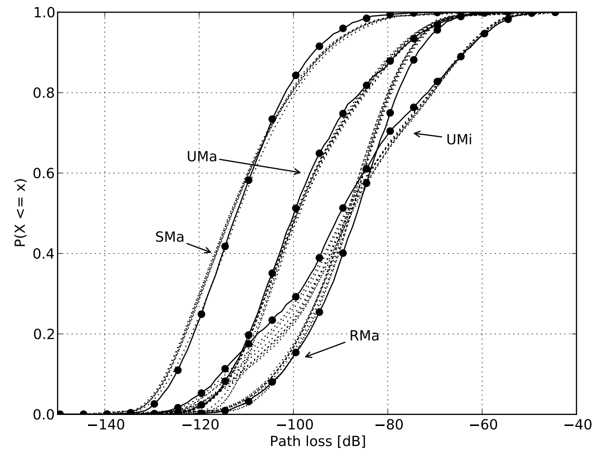


Fig. 4. CDFs of path loss resulting from our capacity model (solid curves marked with dots) compared to reference results for the four IMT-A deployment scenarios [4]

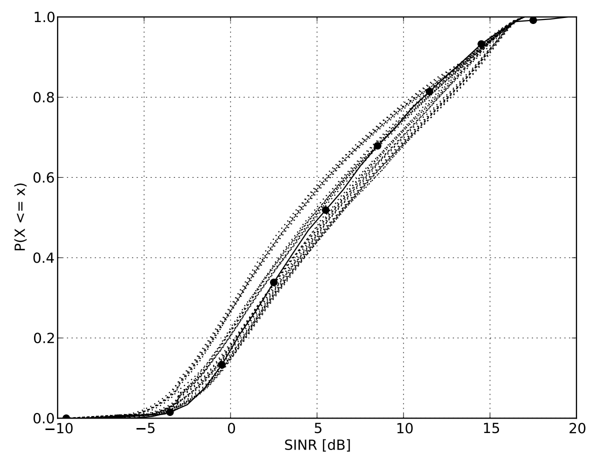


Fig. 5. CDF of SINR resulting from our capacity model (solid curve marked with dots) compared to reference results for the UMa scenario [4]

In Figure 4, the dotted reference graphs show the CDFs of path loss for the four IMT-A deployment scenarios calculated by different partners of the WINNER+ project. The solid graphs marked with big dots represent the results of our numerical capacity model. As can be seen our results match the reference results very well.

The CDFs of the SINR is exemplarily shown for the UMa scenario in Figure 5. Again, a good match of the numerical result (solid line marked with big dots) with the reference results (plotted as dotted lines) is achieved.

We conclude from this that even if the number of BS sites considered in the investigated scenarios is smaller than specified by the IMT-A evaluation guidelines (namely three sites instead of 19) and even if the average number of MSs per BS is reduced (three instead of ten), small differences to the reference results can be expected, only. This gives confidence

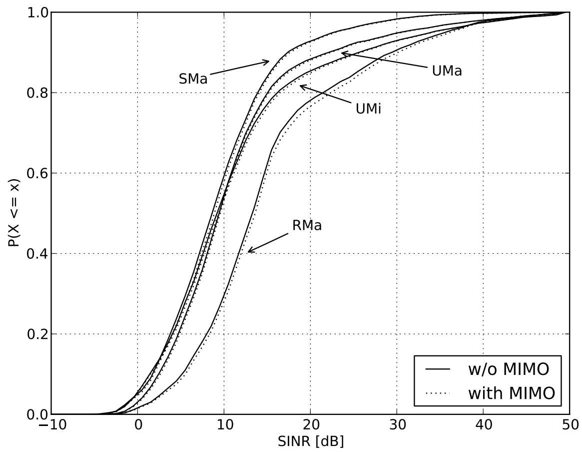


Fig. 6. CDFs of weighted SINRs for the four IMT-A deployment scenarios without MIMO transmission (solid lines) and with MIMO transmission (dotted lines)

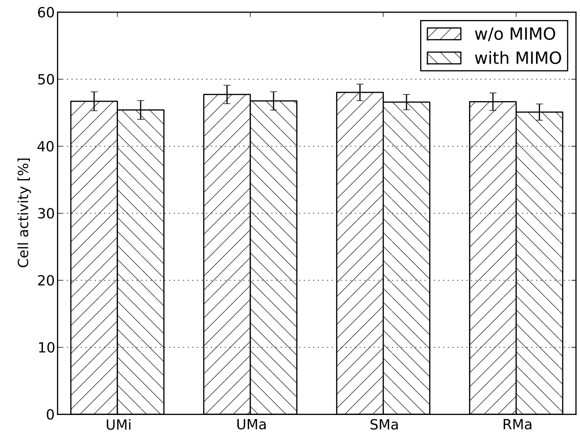


Fig. 7. Percentage of time a cell is active, i.e. the BS within a cell is transmitting

to the assumptions that the upper bound capacity calculated from our model is close to the capacity that can be achieved in a real IMT-A system.

### *B. Numerical Results for IMT-A Capacity*

The schedule calculated by LP determines the durations of the NSs, i.e. the time when transmissions associated to a certain NS are active. The SINRs of the receiving stations in an NS are known from geometries in the model. Thus, by weighting SINRs by the duration of the according NS and calculating the histogram for all NSs of the schedule, the CDF of time weighted SINRs can be determined, see Figure 6. The shapes of the graphs are similar for all scenarios, only for RMa it is slightly shifted to higher SINRs. The solid line graphs are valid for scenarios without MIMO transmission and are quite close to the dotted line graphs representing the same scenarios with 2x2-MIMO transmission. Under an optimal schedule typical SINRs are in the interval from 0 to 20 dB for all scenarios and only a marginal amount of transmissions happen with an SINR of more than 30 dB. Thus, the data rates resulting from link adaptation using Modulation and Coding Schemes (MCSs) of real IMT-A systems will mostly refer to that possible with SINR in the range 0 to 20 dB, with some higher rate if SINR is higher.

The activity percentage of a given cell is shown in Figure 7. A cell is considered active if the BS within the cell is transmitting. For all scenarios the cell activity is about 46-48 % without MIMO and slightly (about one percentage point) lower with MIMO. This result corresponds to the findings in Figure 6: The slightly better SINRs under MIMO transmission improves the data rate a little, thereby causing a slightly reduced cell activity. The mean cell activity is below 50 % indicating that adjacent cells may not be actively transmitting more than 50 % in the optimal schedule to keep interference sufficiently low and thereby maximize system capacity. Since we have evaluated a large number of scenario instances, numerically, the error intervals for a 95 % confidence level are shown, too.

The upper bound cell spectral efficiency for the four scenarios is presented in Figure 8. The first bar for each scenario shows the ITU-R requirement for IMT-A systems. The second and third bars give the evaluation results of the numerical model without and with MIMO transmission.

The uppr bound cell spectral efficiency for the respective ISD (Table I) with MIMO is about 3.6 b/sHz for the UMi and UMa scenarios, 3.2 b/sHz for the SMa scenario and 4.6 b/sHz for the RMa scenario. Thus, with MIMO the IMT-A requirements are met for all four scenarios and related channel models. Without MIMO, only the IMT-A requirements for the RMa scenario are met. Hence, MIMO is essential for future IMT-A systems if no other alternate technologies like Cooperative Multi-Point (CoMP) transmission or relaying [12] is applied.

For some scenarios, the IMT-A requirements are hard to meet. The cell spectral efficiency required for the UMi scenario is 72 % of the upper bound value calculated in our model for rate fair scheduling (without power control). Similar applies for the SMa scenario where the IMT-A requirement is about 68 % of the upper bound value achievable according to our calculations. For the UMa scenario the IMT-A requirement appears to be less rigorous, since it is about 61 % of the upper bound value achievable according to our model. For the RMa scenario the IMT-A requirement appears easy to meet, since about 23 % of the upper bound cell spectral efficiency is required to be IMT-A compliant, only. It is worth noting that a non-optimal scheduler that has only partial oversight on the pending transmissions and the resulting interference, will achieve a lower spectral efficiency than calculated by our model. We have assumed link adaptation according to the Shannon boundary. Hence, we expect that power control will not increase the cell spectral efficiency.

As we assume rate fair scheduling the cell edge user spectral efficiency is identical to the cell spectral efficiency.

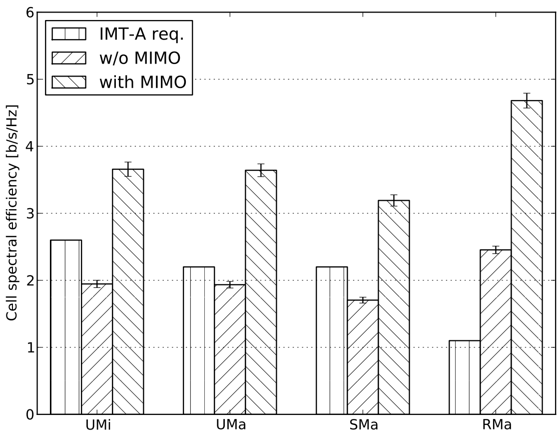


Fig. 8. Cell spectral efficiencies of the four deployment scenarios

Considering the cell edge user spectral efficiency our results exceed the IMT-A requirements by more than one order of magnitude. In case a different scheduling is assumed the cell spectral efficiency might be higher at the expense of a lower cell edge user spectral efficiency.

## V. Conclusions

A model is introduced to calculate numerically the upper bound cell spectral efficiency for IMT-A compliant cell deployment scenarios assuming rate fair scheduling and no power control. The results show that the IMT-A requirements can be met for rate fair scheduling in general, if MIMO transmission is applied. For the UMi, UMa and SMa IMT-A scenarios the requirements appear to be quite ambitious since the upper bound calculated in this paper is not as much higher. The RMa scenario appears less demanding. To maximize cell spectral efficiency IMT-A systems will have to support MCSs able to operate in SINR ranges from 0 to 35 dB. Furthermore, a high degree of coordination for interference avoidance between adjacent cells is required. In summary, all results show that our numerical model delivers useful upper bound results for the cell spectral efficiency of IMT-A systems under the assumptions made.

## References


[1] *IEEE 802.16m System Description Document*, IEEE Std., Rev. 09/0034r3, 2010.

[2] *TS36.300 - Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description*, 3rd Generation Partnership Project Technical Specification, Rev. V10.1.0, 2010, http://www.3gpp.org.

[3] International Telecommunication Union, "ITU paves way for next-generation 4G mobile technologies," Feb. 2011. [Online]. Available: http://www.itu.int/net/pressoffice/press_releases/2010/40.aspx

[4] "Final Evaluation Report from WINNER+ on the IMT-Advanced Proposal in Documents IMT-ADV/6, IMT-ADV/8 and IMT-ADV/9," ITU-R, Tech. Rep. ITU-R IMT-ADV/22, Jun. 2010.

[5] "Evaluation of IMT-Advanced candidate technology submissions in Documents IMT-ADV/4, IMT-ADV/5 and IMT-ADV/7 by WiMAX Forum Evaluation Group," ITU-R, Tech. Rep. ITU-R IMT-ADV/22, Jun. 2010.

[6] S. Max, E. Weiss, and G. Hiertz, "Benefits and limitations of spatial reuse in wireless mesh networks," in *Proceedings of the 10th ACM Symposium on Modeling, Analysis, and Simulation of Wireless and Mobile Systems*. ACM, 2007, pp. 244–251.

[7] J. Luo, C. Rosenberg, and A. Girard, "Engineering wireless mesh networks: Joint scheduling, routing, power control, and rate adaptation," in *IEEE/ACM Transactions on Networking*, vol. 18, no. 5, 2010, pp. 1387–1400.

[8] "Guidelines for evaluation of radio interface technologies for IMT-Advanced," ITU-R, Tech. Rep. ITU-R M.2135, Nov. 2008.

[9] D. Gore, R. Heath, and A. Paulraj, "On performance of the zero forcing receiver in presence of transmit correlation," in *Proceedings of IEEE International Symposium on Information Theory*, 2002, p. 159.

[10] C. Shannon, "A mathematical theory of communication," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 5, no. 1, pp. 3–55, 2001.

[11] S. Toumpis and A. Goldsmith, "Capacity regions for wireless ad hoc networks," *IEEE Transactions on Wireless Communications*, vol. 2, no. 4, pp. 736–748, 2003.

[12] M. Siebert and Z. Liu, "NGMN (r)evolution of mobile radio networks," in *Proceedings of European Wireless 2010 Conference*, 2010, pp. 989–993.