This document is a preprint of: M. Krondorf and G. Fettweis, "Carrier Frequency dependent Downlink Spectral Efficiency of Cellular LTE Deployments," in Proceedings of IEEE International Conference on Communications (ICC 2009), Dresden, Germany, Jun 2009. DOI:10.1109/ICC.2009.5198811

Carrier Frequency dependent Downlink Spectral Efficiency of Cellular LTE Deployments

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***Abstract*—This paper explains a system level evaluation framework which allows performance assessment of cellular OFDM-based systems at different carrier frequencies. In the numerical examples we model the downlink transmission of an 3GPP LTE deployment.**

I. Introduction

Spectral efficiency is known to be the figure of merit for mobile operators. In this paper we explain how to compute the spectral efficiency and area spectral efficiency of an cellular LTE deployment which is operated at different carrier frequencies. The framework is in particular relevant for decision makers who have to evaluate certain bands concerning their economic relevance. In the course of the paper we explain the underlying link and system level concepts and we explain how to derive the spectral efficiency based on link level performance metrics. Our study is based on simplified LTE downlink PHY assumptions, where we assume an OFDM-TDD MAC instead of the OFDMA medium access scheme, i.e. all links use the entire bandwidth in a time slotted manner. The interested reader is referred to the LTE system concept explanations given in [5] and the references therein for further reading.

II. LTE System Model

A. LTE Link Level Model

LTE uses OFDM modulation in the downlink which can be effectively described by means of a frequency domain baseband signal model as follows:

$$Y_l = X_l H_l + W_l \quad \text{where} \quad Z_l = \frac{Y_l}{\hat{H}_l}. \tag{1}$$

Here, Y_l denotes the received signal on subcarrier l while the factor H_l represents the channel transfer function respectively. W_l is the additive Gaussian noise component. Correct time and frequency synchronization is assumed in (1). Subcarrier-wise equalization is done in a zero-forcing manner, using the channel estimates $\hat{H}_l$. From equalization we finally obtain the decision variables Z_l which are then fed in the detector/decoder stage.

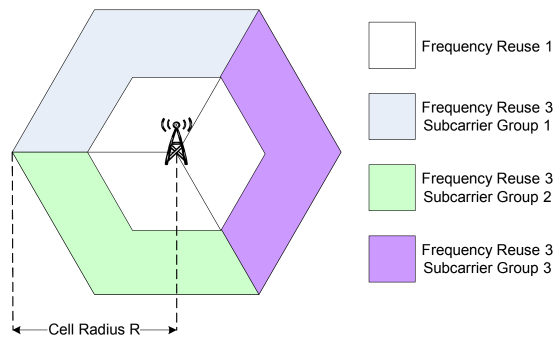

Fig. 1. LTE cell with FFR and threefold sectorization

The random variable Z_l can be analytically described by its conditional PDF

$$p_{Z_l}(z|X).$$

The authors derived $p_{Z_l}(z|X)$ for a high number of OFDM configurations, channel estimation schemes and fading channel properties which can be found e.g. in [1] and [2]. Specifically, $p_{Z_l}(z|X)$ captures the effects of channel estimation errors and outdated channel state information (CSI) induced by user mobility.

Based on $p_{Z_l}(z|X)$, the ergodic data rate in terms of mutual information serves an important link level performance metric which can be calculated subcarrier-wise:

$$\begin{aligned} R_l \;=\; & \sum_m P(X_m) \int_{Z_r}\int_{Z_i} p_{Z_l}(z_r + jz_i|X_m) \\ & \times \log_2\left(\frac{p_{Z_l}(z_r + jz_i|X_m)}{\sum_n p_{Z_l}(z_r + jz_i|X_n)P(X_n)}\right) dz_r dz_i. \end{aligned} \tag{2}$$

B. LTE System Level Model

Typically, system level evaluation campaigns are closely linked with radio cell modeling where hexagonal or circle shaped cells are assumed. A hexagonal LTE radio cell is depicted in Fig.1, where three important aspects are to be mentioned: *sectorization*, *fractional frequency reuse* (FFR) and *system load*.

Sectorization: Here, directional antennas are used to divide up a base stations 360° radiation field into N_S sectors, where

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N_S is typically chosen to 3. This reduces the number of first tier interfering cells from 6 to 2 and we assume that there is no inter-sector interference present inside the cell. Due to the TDD MAC assumption only one link per sector is active in each time instant.

Fractional frequency reuse - FFR: Typically, LTE and WiMAX deployments are frequency reuse one systems where the entire band is used in each cell. Since inter-cell interference is a major concern in reuse one deployments, FFR divides the cell area into two reuse regions. The inner region uses a frequency reuse factor of one where the entire band, i.e., all available subcarriers, are allocated. Conversely, the outer cell regions exhibit a frequency reuse of 3, where only one third of the available resources are used, mainly to prevent cell edge users from harmful interference. As a result, the maximum possible link throughput in the outer cell area is only $1/3$ of the inner one and the outer spectral efficiency is reduced by the factor $1/3$ as well. In the following we use the FFR ratio μ to quantify the ratio between the inner reuse one cell area A_1 and the total cell area A_{cell}:

$$\mu = A_1/A_{\text{cell}}.$$

System Load: In a fully loaded system, all frequency resources, i.e., subcarriers, are used in all sectors in every time instant, which leads to maximum possible interference. In a partially loaded system, the activity per sector is modeled as an ON-OFF process which is independent among the sectors. Here, the ON-probability is defined by means of a given *load factor* ρ ranging from 0 to 1.

User Random Location Model: User placement is an important task in system level simulations which can be facilitated if environmental and building data can be used, i.e., the placement of houses, streets etc. . Since the intention of our system level campaign is to show general tendencies and performance trends, no detailed location data is used and a uniform user distribution over the area is assumed. Polar coordinates are used to place users inside their respective sectors, where the phase β and the mobile-to-base station distance r are modeled as random variables having the following PDFs as taken from [6]:

$$p_\beta(\beta) = \frac{3}{2\pi}, \qquad -\frac{\pi}{3} \leq \beta \leq \frac{\pi}{3} \tag{3}$$

$$p_R(r) = \frac{2(r-R_0)}{(R-R_0)^2}, \qquad R_0 \leq r \leq R. \tag{4}$$

Here R_0 is the closest possible mobile-to-BS distance which is chosen to be 30 meters within our evaluations. The statistics $p_\beta(\beta)$ and $p_R(r)$ result in a uniform user distribution in a sector of $120°$, where the radio cell is approximated to be circle shaped with radius R.

Tx Power Control: We consider a rather simple transmit power control scheme where the distance attenuation due to path loss and shadowing is inverted in order to reach a target SNR γ_{target}. Hence, the linear scale transmit power P_{Tx} has to be adjusted according to the following rule:

$$P_{\text{Tx}} = \gamma_{\text{target}} \frac{\sigma_W^2}{P_{\text{loss}}(d)}, \tag{5}$$

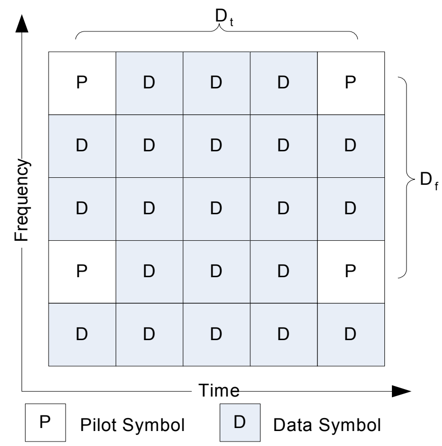

Fig. 2. OFDM time frequency grid

where $P_{\text{Tx}} \leq P_{\text{Tx,max}}$ to not exceed the maximum transmit powers set by the frequency regulation authorities. The noise power σ_W^2 is typically taken from link budget considerations whereas the path loss $P_{\text{loss}}(d)$ at distance d is obtained from pilot signal based CQI (channel quality indicator) measurements. The target SNR γ_{target} typically incorporates margins for fast fading and inter-cell interference and is set to be $\gamma_{\text{target}} = 30$ dB in the numerical examples given in this paper.

III. Spectral Efficiency - From Link to System Level Performance Metrics

The LTE PHY is modeled as block-oriented OFDM transmission as depicted in Fig.2. Pilot symbols are inserted, having a frequency and time separation of D_f and D_t respectively. Two dimensional channel interpolation is assumed as explained in our previous work [2]. In the following we will derive link and system level performance metrics which are required for LTE performance assessment.

A. Link Level Performance Metrics

Link level performance metrics are inevitable parts for any kind of system level performance evaluation campaign. In this paper we choose the ergodic rate R_l on carrier l as performance metric, where we now extend the notation towards the OFDM symbol index n:

$$R(n, l, f_{\text{D,norm}}, \gamma).$$

Here, we also include the normalized Doppler frequency $f_{\text{D,norm}}$ and the average subcarrier SNR γ. Both parameters are well captured by the conditional PDF $p_{Z_l}(z|X)$ which is used in (2) for rate computation. The normalized Doppler frequency directly includes the user mobility v and the carrier frequency f_c of the system and is given by

$$f_{\text{D,norm}} = \frac{v}{c} f_c T_{\text{Sym}},$$

where c denotes the speed of light and T_{Sym} represents the OFDM symbol duration. The channel is assumed to exhibit a Jakes' spectrum, i.e. the channel auto-correlation is given by the well known Bessel function term.

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Number of used carriers N_C	83 (128 FFT)
Subcarrier spacing	15kHz
OFDM block length N_B	7 OFDM symbols
maximum P_{Tx} per antenna element	21 dBm (BS), 20 dBm (MT)
Num. of antenna elements	2 (BS), 1 (MT)
antenna gain	15 dBi (BS), -1 dBi (MT)
Noise Figure	4 dB (BS), 7 dB (MT)
Fast fading margin	2 dB
Interference margin	3 dB
Thermal noise	-174 dBm/Hz
Min. required SINR γ_{min}	0 dB

TABLE I
LTE LINK BUDGET

Since each OFDM block consists of N_B OFDM symbols, each allocating N_C carriers, we now define the throughput per OFDM block as:

$$T(\gamma, f_{\text{D,norm}}) = \frac{\sum_n \sum_l R(n, l, f_{\text{D,norm}}, \gamma)}{N_C N_B},$$

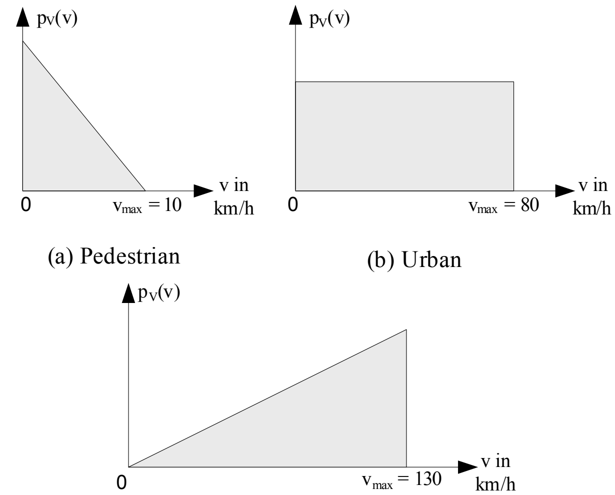
where $R_l(\mu, f_{\text{D,norm}}, \gamma)$ is set to zero at any pilot position (l, μ). Hence, $T(\gamma, f_{\text{D,norm}})$ can be interpreted as the average throughput of the smallest OFDM resource unit that greatly depends on $f_{\text{D,norm}}$ and the used pilot pattern.
Four different pilot patterns are considered for different pilot carrier separations D_f in the frequency direction: (1) Preamble only, (2) Preamble-Postamble, (3) Preamble-Midamble-Postamble and (4) Midamble only. Hence, we write in the following $T_\kappa(\gamma, f_{\text{D,norm}}, D_f)$, where κ denotes the index of the pilot pattern with $\kappa \in \{1, 2, 3, 4\}$. In the next step we eliminate the pilot dependency at different $f_{\text{D,norm}}$ and obtain the throughput $T_{\text{max}}(\gamma, f_{\text{D,norm}})$ maximized over all pilot patterns and possible D_f:

$$T_{\text{max}}(\gamma, f_{\text{D,norm}}) = \arg \max_{\kappa, D_f} \{T_\kappa(\gamma, f_{\text{D,norm}}, D_f)\}, \quad (6)$$

which can be found by numerical brute force search.
Since the normalized Doppler frequency is given by $f_{\text{D,norm}} = f_{\text{D,max}} T_{\text{Sym}}$ where $f_{\text{D,max}}$ in turn depends on the user velocity v and used carrier frequency f_c as $f_{\text{D,max}}(v, f_c) = \frac{v}{c} f_c$, we have that $T_{\text{max}}(\gamma, f_{\text{D,norm}}(v, f_c))$ becomes a random variable due to stochastic v.
Finally, we end up with the carrier frequency dependent throughput $T_{\text{max}}(\gamma, f_c)$ averaged over the user mobility PDF $p_V(v)$:

$$T_{\text{max}}(\gamma, f_c) = \int_0^{v_{\text{max}}} T_{\text{max}}(\gamma, f_{\text{D,norm}}(v, f_c)) \; p_V(v) \; dv \; . \quad (7)$$

For performance evaluation we consider three typical velocity distributions (’*Pedestrian*’, ’*Urban*’, ’*High Velocity*’) as given in Fig.3. We used easy to implement triangular and rectangular shaped density functions that are well defined by v_{max}. Note that the link budget parameters of Tab.I are used throughout our investigations.



(a) Pedestrian (b) Urban (c) High Velocity

Fig. 3. User velocity profiles

B. System Level Performance Metrics

We use the following operation to obtain the average (maximum) throughput per carrier:

$$T_{\text{max}}(f_c, \rho, \mu) \;=\; \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} T_{\text{max}}(\gamma, f_c) \; p_\gamma(\gamma | f_c, \rho, \mu) \; d\gamma \; . \quad (8)$$

Here, $p_\gamma(\gamma | f_c, \rho, \mu)$ denotes the PDF of the SINR, where the distribution includes both thermal noise effects and inter-cell interference. The SINR statistic is a conditional PDF depending on f_c, the system load ρ and the FFR ratio μ. This is because the inter-cell interference directly depends on the traffic in the neighboring cells, on the frequency dependent path loss and on the cell size which is also frequency dependent.
While the user velocity profile $p_V(v)$ is taken from Fig.3, the SINR statistic $p_\gamma(\gamma | f_c, \rho, \mu)$ is obtained from Monte Carlo simulation of the cellular deployment as it will be explained in Sec.III-C. From $T_{\text{max}}(f_c, \rho, \mu)$ we can now derive the spectral efficiency per carrier per site, taking into account the system load ρ, the threefold sectorization and the FFR ratio μ. Therefore we extend the notation of $T_{\text{max}}(f_c, \rho, \mu)$ to make a distinction between the throughput obtained in the inner reuse one cell area and the outer reuse three cell area:

$$T_{\text{max},1}(f_c, \rho, \mu) \quad \text{and} \quad T_{\text{max},3}(f_c, \rho, \mu).$$

The carrier frequency dependent spectral efficiency per subcarrier per site $T(f_c, \rho, \mu)$ is now determined by the following equation:

$$T(f_c, \rho, \mu) = \underbrace{N_S \; \underbrace{\rho \left(\mu T_{\text{max},1}(f_c, \rho) + \frac{1}{3}(1 - \mu) T_{\text{max},3}(f_c, \rho) \right)}_{\text{Spectral Efficiency per Sector}}}_{\text{Spectral Efficiency per Site}}, \quad (9)$$

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where N_S denotes the number of sectors per cell. From $T(f_c, \rho, \mu)$ it is straight forward to derive the *area spectral efficiency* T_{area} which is defined as:

$$T_{\text{area}}(f_c, \rho, \mu) = \frac{T(f_c, \rho, \mu)}{A_{\text{cell}}} \ .$$

The area spectral efficiency is of major concern for mobile operators because it directly reflects the amount of user data which can be supported by the system per unit area. T_{area} scales with f_c and hence directly enables operators to trade base station density and deployment costs versus revenue per unit data for a given user density.

C. SINR Statistics of LTE Cellular Deployments

The Monte Carlo simulation of $p_\gamma(\gamma|f_c, \rho, \mu)$ is described in this section where the following factors influence the instantaneous subcarrier SINR γ: inter-cell interference, random location of mobile users, path loss, shadowing and cell size. The instantaneous SINR is given by

$$\gamma = \frac{P_{\text{loss}}(d)P_{\text{Tx}}}{\sum_k P_{\text{loss}}(d_k)P_{\text{Tx}}(k) + \sigma_W^2} \ . \qquad (10)$$

The variance σ_W^2 denotes the AWGN noise power, accounting for thermal noise and noise figure contributions. The path loss model is assumed to account for distance signal attenuation, log-normal shadowing and the carrier frequency. In this paper we use the WINNER path loss specifications which can be found in [3]. Fast fading effects are not captured here because they are already taken into account in the ergodic throughput metric $T_{\max}(\gamma, f_{\text{D,norm}}(v, f_c))$ used for spectral efficiency calculations. Before running the SINR PDF simulation, the cell radius R as well as the thermal noise power σ_W^2 are to be calculated from the LTE link budget given in Tab.I. Subsequently, the following steps are required in each of the iterations to obtain the SINR PDF of an downlink scenario:

1) The position of the desired mobile is randomly picked according to the location model introduced before.
2) The coordinates of other mobiles are randomly picked in every sector of each interfering cell.
3) Randomly choose which of the DL connections actually create interference based on the FFR, the mobiles' locations and the system load ρ.
4) Calculate the distances between the interfering BS antennas and the desired mobile.
5) Determine the transmit power for each link in the system using the power control scheme already introduced.
6) Calculate the path losses based on the calculated distances.
7) Evaluate the instantaneous SINR from (10).

IV. Carrier Frequency dependent System Scaling

A. Cell Size Scaling

The cell coverage area in a cellular system is defined as the expected percentage of locations within a cell where the received power is above a given minimum. Here, the expectation is due to shadowing variations along the signal path where the desired coverage C, the transmit power and the path loss rules are to be taken into account. Although we approximate the radio cell as circle shaped, the instantaneous cell exhibit an amoeba-like structure due to random shadowing. It should be noted that for cell size computations, *uplink*

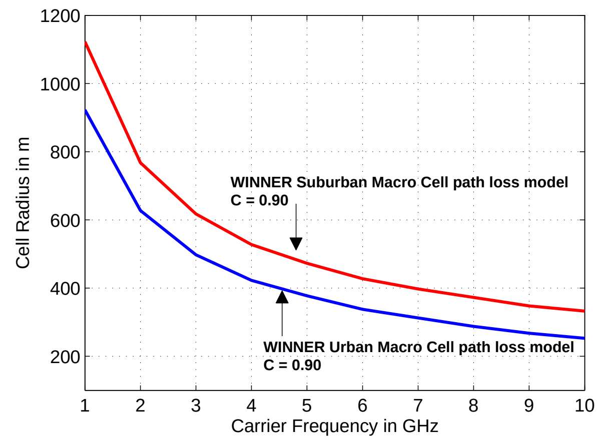

Fig. 4. Cell Radius scaling for Suburban Macro Cell and Urban Macro Cell path loss models.

link budget parameters are to be used. This is mainly because of the mobile terminal's lower maximum transmit power. A. Goldsmith explains in [4] how to calculate the cell coverage $C(R)$ as a function of the cell radius R. Hence, numerical inversion of $C(R)$ can be used to obtain the cell radius $R(C)$ for a desired coverage C. In Fig.4 we depict the cell radius R vs. f_c for the WINNER Urban Macro Cell and Suburban Macro Cell propagation models and for C = 90% .

B. System Load Scaling

The frequency dependent scaling of the cellular deployment, i.e., the change of relevant parameters such as the cell size and the cell load, is of major concern for system level evaluations which is detailed within the following reasoning:

- The frequency dependent cell radius $R(f_c)$ decreases with increasing carrier frequency f_c.
- There is a quadratic decay of the cell area $A(f_c) = \pi R^2(f_c)$ with decreasing cell radius and increasing carrier frequency.
- The user density as well as the average traffic per user can be seen as constant parameters of a given cellular scenario. Hence, at the same user density and constant traffic per user we observe a decaying load $\rho(f_c)$, which decreases proportional to the cell area $A(f_c)$.
- For each cellular scenario we can define a reference cell size A_{ref} and hence a reference frequency f_{ref} at which the reference load is defined to be one[1], i.e., $\rho(f_{\text{ref}}) = 1$, based on the given user density and traffic parameters.
- Hence, there is a decaying load at increasing carrier frequency. Since the operator tries to fully supply the

[1]Real world system are typically dimensioned for system loads below 1 in order to account for varying traffic conditions, e.g., peak hours, depending on the daytime. Since time dependent traffic conditions are not modeled, the reference load $\rho(f_{\text{ref}})$ is kept to be one.

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user traffic demands, the load stays 1 and the cell size does not further scales up if f_c falls below f_{ref}:

$$A(f_c) = A_{ref} \quad \text{and} \quad \rho(f_c) = 1 \quad \text{if} \quad f_c \leq f_{ref}.$$

- Finally, we have to conclude that there is a *frequency dependent scaling factor* $s(f_c)$ ranging from 1 to 0 such that $A(f_c) = s(f_c)A_{ref}$ and consequently $\rho(f_c) = s(f_c)\rho(f_{ref}) = s(f_c)$.

Based on the above given reasoning we now can introduce the following procedure of how to calculate the system scaling factor $s(f_c)$:

1) Define the reference frequency f_{ref} of the system;
2) Calculate the reference cell area $A_{ref} = A(f_{ref}) = \pi R^2(f_{ref})$;
3) $s(f_c) = 1$ and $A(f_c) = A_{ref}$ for all frequencies $f_c \leq f_{ref}$;
4) For all frequencies $f_c > f_{ref}$ we have that $s(f_c) = \frac{A(f_c)}{A_{ref}}$.

Due to the fact that the choice of the reference frequency plays such an important role for the entire system evaluation process, we define two scenarios *Suburban LTE* and *Urban LTE* in Tab.II, each possessing its own propagation model and load situations. In Fig.5 and Fig.6 we depict the scaling factor $s(f_c)$ and the cell area $A(f_c)$ as they are used in the remainder of this paper.

	Suburban LTE	**Urban LTE**
WINNER path loss model	Suburban Macro	Urban Macro
f_{ref}	1 GHz	3 GHz
R_{ref} at C = 0.90	1123m	497 m

TABLE II
LTE SCENARIO DEFINITION

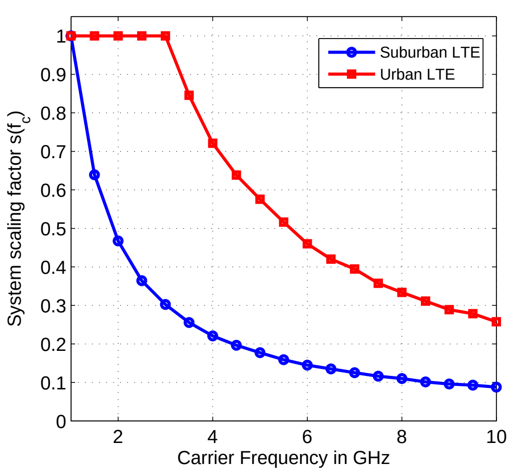

Fig. 5. System load scaling for the Suburban LTE and the Urban LTE scenario.

V. SPECTRAL EFFICIENCY - NUMERICAL RESULTS

The spectral efficiency $T(f_c, \rho, \mu)$ of a given cellular deployment considers the system throughput in the two FFR cell regions as well as the frequency-specific system load $\rho(f_c)$ and the FFR ratio μ according to (9). A threefold sectorization is assumed and the system load is inherently frequency dependent as depicted in Fig.5. Hence we reduce the notation from $T(f_c, \rho, \mu)$ to $T(f_c, \mu)$ in the following. Three rings of interfering cells are used for SINR simulation.

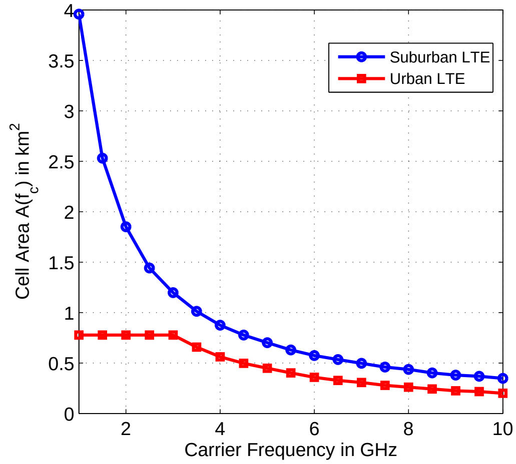

Fig. 6. Cell area scaling for the Suburban LTE and the Urban LTE scenario.

A. *Spectral Efficiency vs. FFR ratio* μ

In Fig.7 we depict the downlink spectral efficiency in bit/subcarrier/site vs. μ for the Urban LTE scenario, where the pedestrian velocity profile is used. The results illustrate that there is a spectral efficiency maximizing FFR ratio for each carrier frequency. In real cellular deployments, mobile operators use site and network planning tools to maximize spectral efficiency in each individual cell. The network/site planning is modeled in our system level evaluation campaign by the following operation:

$$T(f_c) = \arg\max_{\mu} \{T(f_c, \mu)\}, \tag{11}$$

i.e., the best suited FFR ratio is chosen for each carrier frequency.

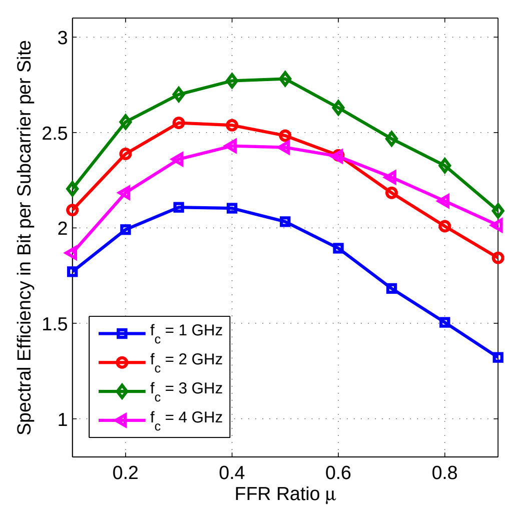

Fig. 7. Downlink spectral efficiency vs. FFR ratio μ for the *Urban LTE* scenario

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B. Spectral Efficiency vs. Carrier Frequency

In Fig.8 and Fig.9 we depict the spectral efficiency $T(f_\mathrm{c})$ for both scenarios Suburban LTE and Urban LTE. It is remarkable that the spectral efficiency exhibits a maximum at the reference frequency f_ref, i.e., at 1 GHz and 3 GHz respectively. For $f_\mathrm{c} < f_\mathrm{ref}$ the Urban LTE spectral efficiency suffers from strong intercell interference. If $f_\mathrm{c} > f_\mathrm{ref}$, the spectral efficiency degrade in both scenarios mainly due to the decreasing system load $\rho(f_\mathrm{c}) = s(f_\mathrm{c}) \cdot \rho_\mathrm{ref} = s(f_\mathrm{c})$.
As expected, higher user mobility does affect the performance in particular at higher carrier frequencies. It is remarkable that high user mobility even leads to a saturation effect of $T_\mathrm{area}(f_\mathrm{c})$ in the Suburban LTE scenario as depicted in Fig.10.

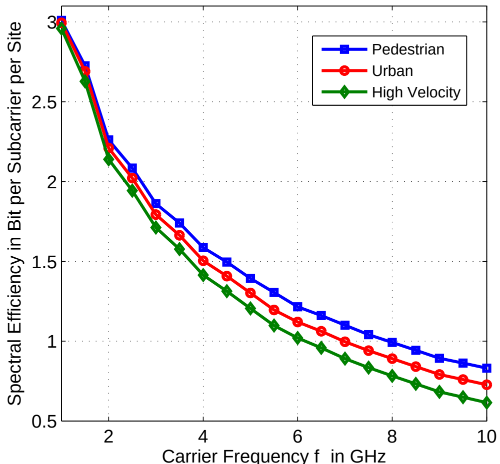

Fig. 8. Downlink spectral efficiency vs. f_c for the *Suburban LTE* scenario.

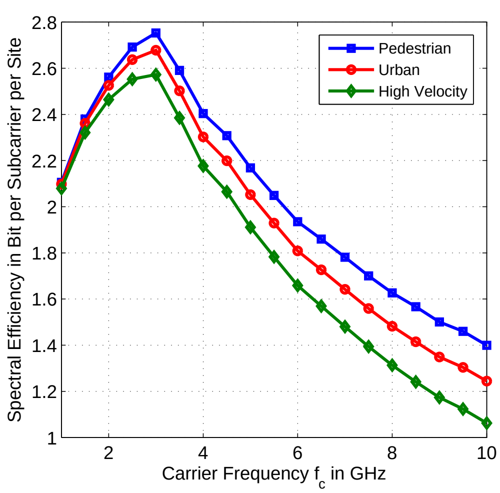

Fig. 9. Downlink spectral efficiency vs. f_c for the *Urban LTE* scenario

C. Performance Loss due to suboptimum Pilot Grids

In Fig.10 the spectral efficiency loss is illustrated which arises, if the pilot pattern is not adapted according to the instantaneous user velocity v. Here, the dashed lines represent the spectral efficiency where the *Preamble-Postamble* pilot pattern is chosen together with a pilot carrier distance of $D_f = 2$. The solid lines in Fig.10 depict the downlink area spectral efficiencies if the pilot pattern is adapted according to the instantaneous user velocity as described in equation (6).

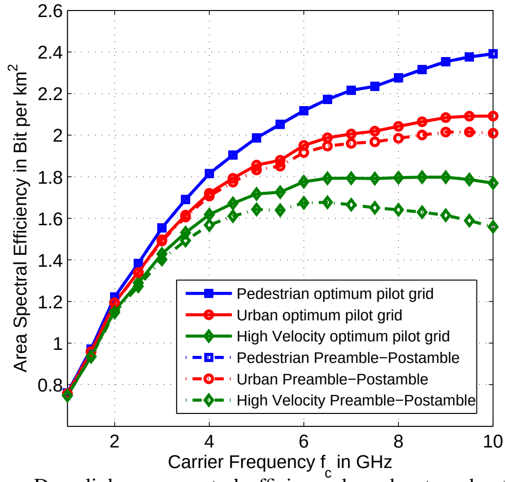

Fig. 10. Downlink area spectral efficiency loss due to suboptimum pilot grids in the Suburban LTE scenario.

VI. CONCLUSIONS

In this paper we extend an existing OFDM link level performance evaluation framework toward system level aspects. The frequency dependency of various system parameters such as cell size, system load and path loss, is identified and modeled accordingly.
Moreover, we have to conclude that system level metrics clearly depend on the system's carrier frequency and on the user's velocity profile. There is a notion of a *best suited carrier frequency*, at least in terms of spectral efficiency. This optimum is closely linked with the expected system load, i.e., the traffic per user and user density of a particular area.
Finally, the presented results hint the necessity of *frequency agile cellular systems* - a novel paradigm of how to distribute frequency licenses. Such flexible frequency assignment and *frequency leasing* schemes are discussed within the Cognitive Radio community [7], and would allow operators to optimally react on changing user/traffic densities or velocity profiles in a well defined geographical area.

REFERENCES

[1] M. Krondorf and G. Fettweis. *OFDM Link Performance Analysis under Various Receiver Impairments*. Article appeared in EURASIP Journal on Wireless Communications and Networking, Hindawi Publishing Corporation, 2007.

[2] M. Krondorf, and G. Fettweis. *Carrier Frequency dependent Throughput Analysis for impaired OFDM Links under User Mobility.* . In Proc. IEEE International Symposium On Personal, Indoor And Mobile Radio Communications (PIMRC'08), Cannes, France, September 2008.

[3] The WINNER consortium, WP5. *D5.4 - Final Report on Link Level and System Level Channel Models*. Public WINNER deliverable, online available: www.ist-winner.org, November 2005.

[4] A. Goldsmith. *Wireless Communications*. New York: Cambridge University Press, 2005.

[5] J. Zyren. *Overview of the 3GPP Long Term Evolution Physical Layer*. Freescale white paper, online available, July 2007.

[6] M. S. Alouini and A. J. Goldsmith. *Area Spectral Efficiency of Cellular Mobile Radio Systems*. IEEE Transactions on Vehicular Technology, Vol.48, No.4, July 1999.

[7] The ORACLE consortium. *ORACLE public deliverable D1.1: Technical Scenarios and Application Scope*. Online available: www.ist-oracle.org September 2006.