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I. Introduction

Numerous publications and talks picture the wireless communication environment of 2020 to be highly heterogeneous in various categories, such as connected device types, service characteristics and propagation environments. To efficiently support this heterogeneity, the air interface for 5G should be configurable to a very high extent. On the physical layer, this configurability should include numerology and frame design with pilot placement and transmission time interval (TTI) length being adjustable to the diverse needs of the respective 5G use case. Numerology incorporates subcarrier spacing and symbol body duration, which are inversely related. Additional temporal protection, such as cyclic prefix (CP), against channel delay spreads is relatively shorter for longer symbol bodies.

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Subcarrier spacing – how to make use of this degree of freedom

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Abstract—This paper provides indications and simulative performance evaluations of how a wireless system can profit from being able to support various subcarrier spacings concurrently. We show that with using this degree of freedom high Doppler, low latency and extended coverage scenarios are improved. In our investigations we consider different options for multi-carrier numerology, frame design and pilot placement. Based on our investigation results and general considerations we propose a set of numerology settings for 5G. Furthermore we propose a tiling concept, enabling the parallel usage of different user-specific numerologies.

Keywords—5G; air interface; multicarrier; subcarrier spacing, Doppler spread; delay spread

I. INTRODUCTION

Numerous publications and talks picture the wireless communication environment of 2020 to be highly heterogeneous in various categories, such as connected device types, service characteristics and propagation environments. To efficiently support this heterogeneity, the air interface for 5G should be configurable to a very high extent. On the physical layer, this configurability should include multi-carrier numerology and frame design with pilot placement and transmission time interval (TTI) length being adjustable to the diverse needs of the respective 5G use case. Numerology incorporates subcarrier spacing and symbol body duration, which are inversely related. Additional temporal protection, such as cyclic prefix (CP), against channel delay spreads is relatively shorter for longer symbol bodies.

The choice of the numerology is driven by the propagation environment to be supported in conjunction with the service needs and the necessary degrees of freedom for control signaling elements, such as pilot symbols.

LTE and other existing wireless communication systems applying multicarrier modulations restrict data transmission using a single predefined subcarrier spacing. The typical numerology choice of LTE with 15 kHz subcarrier spacing with 1 ms TTI is a good compromise for LTE's propagation environment and service needs. Exceptions of this rule are the uplink physical random access channel (PRACH) and downlink multicast/broadcast allocations (MBMS). For the former to accommodate very large cells a much smaller spacing of 1.25 kHz is used. For efficiency reasons the

uplink PRACH is frequency multiplexed with the data (PUSCH) and control (PUCCH) channels. In case of downlink MBMS, a different numerology set, tailored to longer delay spreads appearing in the single frequency network (SFN) setting, may be multiplexed in time. The CP-OFDM waveform of LTE (or its DFT-precoded uplink SC-FDMA variant) prefers a single numerology at one time instant for avoiding inter-carrier interference or larger guard bands. Note that this time multiplex of MBMS restricts achievable unicast latency and also is not very flexible. In general, 5G air interface ambitious latency targets (proposed is e.g. 1ms overall round-trip air interface latency [1]) cannot be fulfilled with LTE 1ms TTI lengths. (This is because we have to consider e.g. downlink data transmission, downlink processing time, ACK/NACK transmission and uplink processing time which in total scales as a multiple of the TTI duration.)

Another target of 5G is to support velocities up to 500 km/h. Here the LTE pilot density in time is not sufficient any more.

For those reasons it is clear that 5G needs a redesign of the frame structure, demanding also for reconsidering of the subcarrier spacing. In [2] we have shown how a wireless system applying multicarrier modulations can support various spacings being frequency multiplexed with tolerable interference levels. This especially holds when new 5G waveforms, such as UF-OFDM are considered which offer an improved spectral localization over CP-OFDM and thus a better support of user/service-specific numerology. Shorter multi-carrier symbols are beneficial for high Doppler and low latency targets. Longer multi-carrier symbols are attractive for extended coverage and high delay spread scenarios. These diverse needs should be handled by user-specific configuration of numerology and pilots, using a few different parameter sets covering the 5G corner cases.

In this paper, we primarily discuss the low latency and high Doppler use cases and touch upon the extended coverage aspect. The benchmark case (addressed in section II) is the LTE physical resource block configuration. Our investigation includes the impact of channel estimation; the respective spectral efficiency performance metric is discussed in III. We then introduce new potential 5G numerology and frame design options, discuss them and evaluate their link level spectral efficiency performance in section IV. Furthermore, we will discuss numerology design

principles their motivation in general for 5G and will present a *tiling concept* for appropriately placing user-specific numerologies into the radio frame. Based on the discussed design principles, example numerology values will be provided in section V. The paper ends with the conclusions we have drawn in section VI. Our findings, based on the provided simulation results, provide a holistic configurable frame design concept for a flexible 5G air interface.

II. BASELINE SETUP AND DISCUSSION

As basic setup we use the frame structure settings of LTE uplink. Fig. 1 depicts the respective structure of a single resource block including the respective pilot placement. The most important aspect to note here is the distance between the pilot columns of 0.5 ms. The relative overhead is 1/7. In contrast to LTE, we base our investigations on UF-OFDM (e.g. [2][3] and references therein).

For estimating the channel we use the following 2-stage procedure (after having estimated the channel coefficients at the pilot positions using the known pilot sequences):

1. Block moving average (with window size G) in frequency direction for noise smoothing.

The channel estimate after this processing step at a given subcarrier is the average of all channel estimates within a window of width G . The window is placed having the currently processed subcarrier in the center of it. The width of the window depends on the coherence bandwidth of the channel.

2. 1-D MMSE filtering:

$$\hat{H}_{j,i} = \mathbf{w}_i \begin{bmatrix} \hat{H}_{j,i_1} \\ \hat{H}_{j,i_2} \end{bmatrix} \quad (1)$$

$\hat{H}_{j,i}$ is the estimated channel coefficient at subcarrier j ($j \in [1 \dots J]$ with J being the width of the allocation in number of subcarriers) in multicarrier symbol i ($i \in [1 \dots I]$ with I being the length of the allocation in number of multicarrier symbols, LTE: $I=14$). $\hat{H}_{j,i_1}$ and $\hat{H}_{j,i_2}$ are the estimated channel coefficients at the pilot positions (LTE uplink: $i_1=4$, $i_2=11$) after noise smoothing (with window length G) carried out in the first stage. $\mathbf{w}_i$ is the weight vector of the MMSE filter:

$$\mathbf{w}_i = \begin{bmatrix} \rho_{i,i_1} & \rho_{i,i_2} \end{bmatrix} \left(\begin{bmatrix} 1 & \rho_{i_1,i_2} \\ \rho_{i_1,i_2} & 1 \end{bmatrix} + \frac{\sigma^2}{GE} \mathbf{I}_2 \right)^{-1} \quad (2)$$

$\mathbf{I}_2$ is the 2-by-2 identity matrix, $\frac{E}{\sigma^2}$ is the signal-to-noise ratio (assumed to be known, here), $\rho_{a,b}$ is the correlation coefficient between multicarrier symbols a and b :

$$\rho_{a,b} = J_0(\Delta_{a,b} 2\pi f_d) \quad (3)$$

$J_0(x)$ is the Bessel function of the first kind, $\Delta_{a,b}$ is the time difference between symbol a and symbol b (in seconds) and f_d quantifies the Doppler spread:

$$f_d = \frac{v}{c} f_c \quad (4)$$

v is the relative velocity (assumed to be known, here), c the speed of light and f_c is the carrier frequency.

III. PERFORMANCE METRIC

Let $y_{j,i}$ be the received symbol at a given time instant i in a given subcarrier j :

$$y_{j,i} = H_{j,i} s_{j,i} + z_{j,i} + n_{j,i} \quad (5)$$

$H_{j,i}$, $s_{j,i}$, $z_{j,i}$ and $n_{j,i}$ are the actual channel coefficient, the transmitted symbol, interference (due to Doppler and delay spreads) and a complex AWGN noise sample (zero mean, variance σ^2). With realistic channel estimation we have:

$$H_{j,i} = \hat{H}_{j,i} + e_{j,i} \quad (6)$$

$e_{j,i}$ is the channel estimation error, $\hat{H}_{j,i}$ the estimated channel coefficient. So:

$$y_{j,i} = \underbrace{\hat{H}_{j,i} s_{j,i}}_{\text{useful signal}} + \underbrace{z_{j,i} + n_{j,i} + e_{j,i} s_{j,i}}_{\text{distortion}} \quad (7)$$

Therefore:

$$SINR = \frac{E[|\hat{H}_{j,i} s_{j,i}|^2]}{E[|z_{j,i} + n_{j,i} + e_{j,i} s_{j,i}|^2]} = \frac{E[|\hat{H}_{j,i} s_{j,i}|^2]}{E[|y_{j,i} - \hat{H}_{j,i} s_{j,i}|^2]} \quad (8)$$

$E[x]$ is the expectation value of x . For comparison we plug the measured SINR into Shannon's well known formula to get an indication on the achievable spectral efficiency.

$$SE = \log(1 + SINR) \quad (9)$$

IV. SCENARIOS AND PERFORMANCE RESULTS

A. Very high Doppler spreads

With a device moving at speed v and transmitting/receiving signals at carrier frequency f_c , we see the following impacts with v and f_c respectively:

- Doppler spread increases leading to:

- Inter-carrier interference increases (included in $z_{j,i}$), when channel variation over one multi-carrier symbol becomes non-negligible.
- Coherence time of the channel shrinks leading to:
 - Channel feedback outdates quicker, gains from frequency selective scheduling are shrinking (not treated here)
 - Channel estimation gets worse (assuming a given pilot pattern)

We have two means to deal with the last issue:

1. redesign pilot placements (increase density in time direction at the cost of additional overhead)
2. shorten symbols (i.e. increase spacing leading to increased pilot density in time direction)

The first option has two potential disadvantages: Either we have to increase the relative overhead, or – to keep the relative overhead fixed – we have to decrease the pilot density in frequency direction. The second option shortens the single symbols making them more vulnerable to delay spreads (possible means to deal with this are given in [2]). So, for the assessment of the high velocity scenario we compare the performance of the following numerology and frame design variants:

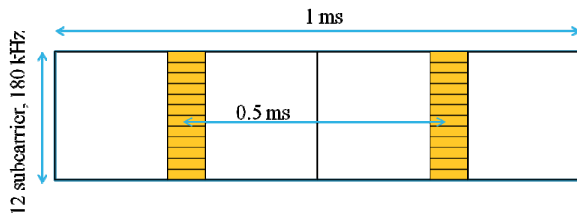


Figure 1 Resource block configuration (LTE UL, PUSCH) – case A

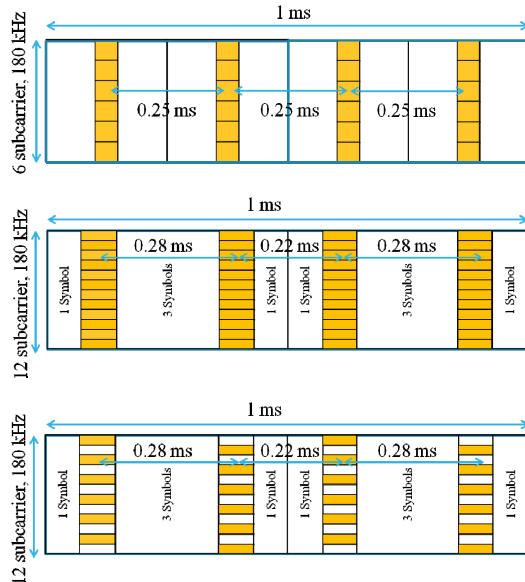


Figure 2 Numerology and frame design options for pilot aided

- LTE-like settings (as given in Fig. 1) – A in the following
- LTE-like pilot placements, but doubled subcarrier spacing, 4 instead of 2 slots (Fig. 2 top) – B in the following
- Modified pilot patterns with doubling the relative overhead to 2/7 (Fig. 2 center) – C in the following
- Modified pilot patterns with keeping the relative overhead (Fig. 2 bottom) – D in the following

The pilots are drawn from Zadoff-Chu sequences. Besides the attractive auto-correlation properties, one of the key reasons for this choice in LTE is the low peak to average power ratio (PAPR) compared to the symbols carrying data. This constant amplitude, zero autocorrelation (CAZAC) property opens the opportunity to boost the pilots in relation to the data. The characteristic of having lower PAPR than symbols carrying data only is destroyed when multiplexing pilots with data in frequency direction (as done in case D). The baseline settings are given in table I.

TABLE I. SETTINGS (LTE-LIKE BASELINE)

parameter	Setting (LTE-like baseline)
Allocation size	6 PRBs á 12 subcarriers, 14 symbols per TTI
Channel model	eTU
Working points (SNR)	[0, 6, 12] dB
Subcarrier spacing	15 kHz
Filter length	74 samples
Sidelobe attenuation	40 dB

We have conducted link level simulations for measuring the SINR as given in (8). Plugging these SINR values into Shannon's formula given in (9) we obtain performance comparison results according to Fig. 3. It becomes apparent that the performance of an LTE-like subframe and numerology setting (case A) severely degrades with high Dopplers (> 500 Hz). By adjusting the subcarrier spacing (case B) this loss can be prevented. Naturally, with low Doppler spreads the original configuration is superior, as here the window for noise smoothing may include more subcarriers for a given frequency width of the window. This calls for enabling the system to choose the respective setting depending on the link characteristic.

Hence, 5G should be able to use a user-specific adaptive numerology for better performance. Increasing the pilot density in time direction and still keeping full pilot symbols without adjusting the density in frequency direction (case C) is able to improve the system for high Doppler spreads as well. However, the higher relative overhead obviously is digging into the overall performance significantly. Finally, increasing the pilot density in time direction with adjusting the density in frequency direction to keep the overhead fixed (case D), so dropping the LTE paradigm of full midamble

pilot symbols, is a good candidate for users with high quality links, though, users with low quality links – e.g. at the cell edge – highly benefit from the opportunity to apply boosting which is not applicable for this case. This is because the data symbols which are in the same multi-carrier symbol as the pilot symbols cause a much higher PAPR, as the well-behaved CAZAC sequences, used in full pilot multi-carrier symbols.

B. Low latency transmissions

Our original motivation to investigate the option of supporting different spacings within a single system has been the one presented above on channel estimation quality. Though, there are even more means to make use of this degree of freedom.

One target of 5G is to support services with very stringent latency requirements. On air interface level the length of the transmission interval is the relevant parameter. For achieving smaller transmission time lengths than the 1 ms LTE reference case, we can either reduce the number of symbols per block (in the following being identified by ‘a’) or shorten the single symbols connected with increasing the subcarrier spacing (in the following being identified by ‘b’) or a combination of both (in the following being identified by ‘c’).

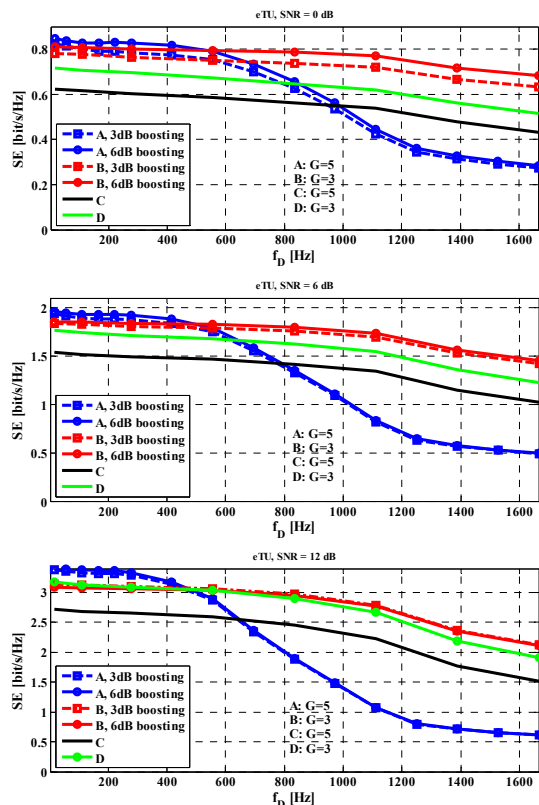


Figure 6 Spectral efficiency as a function of the Doppler spread for various working points (top: 0 dB, center: 6 dB, bottom: 12 dB)

So, we have the different options for designing a resource block with TTI length of 0.5 ms (as given in Fig. 4).

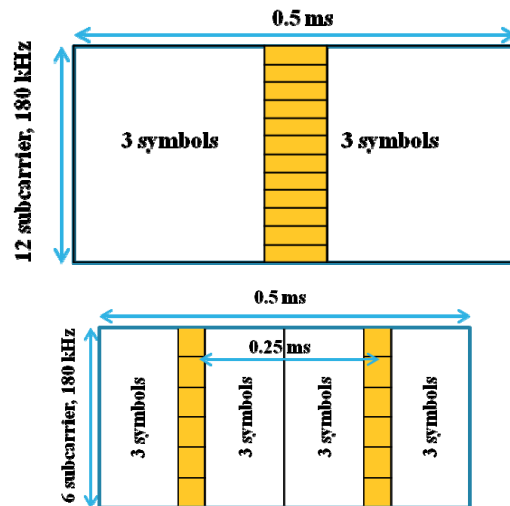


Figure 3 Options for designing TTIs with 0.5 ms duration (top: a, bottom: b).

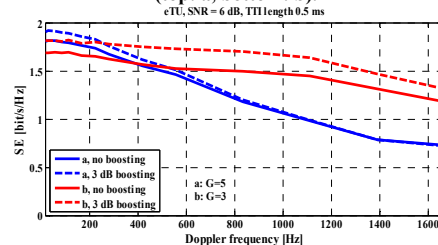


Figure 4 Spectral efficiency as a function of the Doppler spread – options for TTI length of 0.5 ms

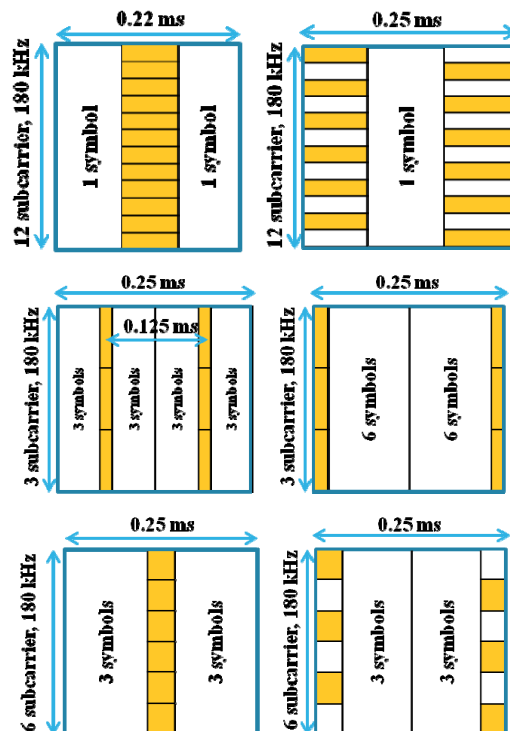


Figure 5 Options for designing TTIs with 0.25 ms duration (top left: a, center: b, bottom: c).

Again we calculate the spectral efficiency as a function of the Doppler spread, illustrated by Fig. 5. Doubling the subcarrier spacing, while keeping the resource block definition (b), is able to produce more stable results for a wide range of Doppler spreads.

Some anticipated use cases for 5G call for even shorter TTIs. So, in the following we investigate means for achieving TTIs with length 0.25 ms (Fig. 6). For each case we have adopted a LTE-like positioning of the pilots and a variant with shifting the pilots to the edge of the resource block (to have less extrapolation and more interpolation).

Fig. 7 indicates: again, just relying on cutting down the number of symbols (a) is inferior to either just adapting the subcarrier spacing (b) or a combination of both degrees of freedom (c).

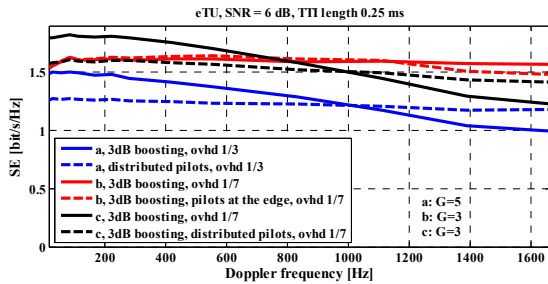


Figure 7 Spectral efficiency as a function of the Doppler spread – options for TTI length of 0.25 ms

C. Extended coverage

One important way to extend coverage is by increasing power spectral density. In case of constrained total transmit power, the consequence is to occupy a smaller bandwidth and stretch the transmission over time. This is also suitable to low end devices (e.g. a massive machine communication (MMC) device), allowing for cheaper narrowband RF front-ends and less energy-consuming D/A and A/D converters.

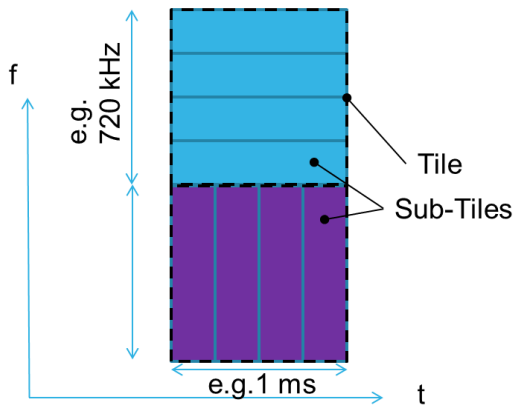


Figure 8 Example illustration of the tiling concept with two different tiles (blue and purple), each applying different TTI lengths (1 ms and 0.25 ms)

When the same forward error correction (FEC) performance is anticipated, the TTI has to extend over time.

We will address such numerology aspects for longer symbol durations in more detail in future publications.

V. DISCUSSION OF 5G NUMEROLOGY CHOICES AND THEIR PARALLEL USAGE

As discussed, 5G needs different numerology sets to support a wide range of carrier frequencies and propagation conditions and to support of shorter TTI length in services with low latency requirements. The LTE sampling rate of 30.72 MHz should be preferably reused in whole-numbered fractions/multiples. Reusing LTE clocking will significantly reduce the development effort for mobile chipsets (as well as reducing chip complexity). For supporting scheduler and layer 2+ alignment, carrier aggregation and cross-carrier scheduling, TTI lengths should be integer fractions (1, 2, 4, 8) or multiples of the 1ms LTE TTI. For handling frequency multiplexing of different TTI lengths in conjunction with different co-existing numerologies, we propose a tiling concept, as depicted in Fig. 8. For keeping overhead constant and code block sizes not too small, shorter (in time) sub-tiles are typically broader in frequency. The tile is the resource-organizing unit for coping with different sub-tile shapes. An appropriate scheduler solution should first allocate the tiles according to current service and propagation demands (on a 1 ms or larger timescale) and then carry out the actual resource block scheduling using the sub-tiles. Our proposed approach thus helps to structure the 2-D resource grid allocation.

5G below 6GHz is the first system which will be introduced on existing carrier frequency bands (today used in e.g. 3G/4G). If coexistence with LTE should be supported with full flexibility, an integer multiple or fraction of the 15 kHz subcarrier spacing would be desirable from an inter-carrier interference perspective, as well as a time-alignment with LTE symbols, using integer fractions or multiples of 1/14 ms. When the number of symbols within 1ms is a power of two, splitting into sub TTI lengths is easy. However, this implies sacrificing the alignment to LTE symbol durations and subcarrier spacings. This is no problem when 4G/5G coexistence on the same carrier is not required and otherwise needs to be investigated.

Section IV performance results have shown that pilot boosting is helpful for roughly 10% spectral efficiency gain. In case we want to use this boosting and the pilot overhead shall not be larger than LTE, we need to have at least 7 multi-carrier symbols per TTI. This gives a center pilot symbol per TTI with e.g. CAZAC properties. Such that ≥ 7 symbols provide reasonable pilot placement. Otherwise, scattered pilots will result in loss of CAZAC properties and/or boosting capabilities. This minimum number of symbols per TTI thus implies increased subcarrier spacing for lower latencies compared to LTE. Such larger subcarrier spacings are also desirable in terms of FFT-complexity, as the number of additions and multiplications grows with $N \log N$, especially as 5G systems will have to support larger carrier bandwidths.

TABLE II REASONABLE NUMEROLOGY SETTINGS FOR 5G

TTI length	0.25 ms	0.25 ms large cell	0.125 ms	0.125 ms large cell	1 ms LTE-like case	2 ms long symbol case (broadcast)
Subcarrier spacing	30 kHz	15 kHz	60 kHz	30 kHz	15 kHz	3.75 kHz
#symb/TTI	7	3	7	3	14	7
Samples/symb	1024 + X	2048 + X	512 + X	1024 + X	2048 + X	8192 + X
Guard time (overhead)	2.38 μ s X = 73 (6.6 %)	16.6 μ s X = 512 (20%)	1.17 μ s X = 36 (6.6%)	8.3 μ s X = 256 (20%)	4.76 μ s X = 146 (6.6%)	19 μ s X = 584 (6.6%)

The LTE CP length of 4.76 μ s may be even slightly over-dimensioned for macro cells. (E.g. latest weak arrivals in Vehicular A channel models are at 2.5 μ s.) Cutting its length by a factor of 2 (corresponding to 30 kHz subcarrier spacing) compared to LTE poses no significant ISI to typical macro cells. In case of DFT-spreading, by ZT-DFTs [4] which is compatible to UF-OFDM, a user-specific delay spread protection can be used in the system, just for the users which will need it. So a further symbol length reduction is possible (factor 4) even with a constant time overhead.

In the absence of DFT-spreading (e.g. in the downlink), when very large cell support with no ISI (for 64 / 256 QAM) is desired, optionally the time guards can be increased, see table II

Our discussed considerations lead to table II as a consequence under the assumption of supporting full in-carrier coexistence of 4G and 5G. (Note that two zero samples need to be added at the end of a 1ms tile, as the LTE sample rate, which emerged from the UMTS chip rate of 3.84 MChip/s cannot be integer-divided by 14. Optionally, different symbol lengths within one TTI can be used for 5G, as in the LTE case.)

VI. CONCLUSIONS

We have investigated to what extent a wireless system can improve by making use of adjustable subcarrier spacings on a per user base. Both high Doppler and low latency scenarios have shown to provide improved performance results, if this degree of freedom is available. In addition coverage extension (e.g. for MMC services with devices being located in the basement) and MBMS services can benefit from this option.

The results in this paper have to be seen in conjunction with [1]. Here, we have shown how different spacings can share the TTI. This improves the flexibility of the system as it is able to use this option in a much finer grained manner and within each TTI. The appropriate frame design for using different adaptive numerologies on the same carrier has been proposed with the presented tiling concept.

Finally, we summarize our view on reasonable numerology settings for 5G in Table II for different TTI

lengths. Preferable option for large cell settings is to use the settings for typical cell sizes and apply user specific zero-tails [4]. This way overhead is significantly reduced.

ACKNOWLEDGMENT

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