Idle period shortening for TDD communications in large cells

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***Abstract*— Time division duplex (TDD) technologies are necessary to deal with unpaired frequency bands and to allow low-complexity user equipments (UE) without duplexer in paired frequency bands. In TDD communications, a frame is divided into several sub-frames, each sub-frame being allocated to either uplink (UL) or downlink (DL). An idle period (IP) is required at a DL/UL switching point. It is usually dimensioned according to the cell radius and is identical for all UEs of the cell. In this paper, we propose a UE-specific IP duration, which increases the overall data rate of TDD communications for large cells. Numerical results show the potentially large benefit of the proposed dimensioning in term of spectral efficiency, which can be obtained without any specific signaling.**

Keywords-component: TDD, idle period, frame design, timing advance, block-wise transmission.

I. INTRODUCTION

For future mobile cellular communication systems, time division duplex (TDD) communications [1], either on a single frequency band or on two separate frequency bands, have been identified as necessary to deal with unpaired bands and to allow low-complexity user equipments (UE) without duplexer in paired bands. In TDD communications, a frame is divided into several sub-frames, each sub-frame being allocated to either uplink (UL) or downlink (DL) communication time. Thereby, TDD systems can flexibly support asymmetric traffic by simply changing the ratio of UL and DL sub-frames in a frame. TDD systems may also offer other benefits such as channel reciprocity between UL and DL, which may be utilized for advanced processing techniques such as pre-filtering, link adaptation or power control.

Idle periods (IP) are required in TDD communications. IPs not only avoid simultaneous reception and transmission in the half-duplex transceiver but also allow synchronous or quasi-synchronous UL transmissions that necessitate timing alignment of UEs' UL sub-frames at the base station (BS). As a result, the active transmission duration is reduced compared to the original sub-frame duration.

Generally, the sub-frame duration is chosen according to the system constraints so as to find a good trade-off between a maximum spectral efficiency and a minimum system latency: Indeed, a long sub-frame duration is suitable for a small overhead of idle period and signaling, whereas a shorter sub-frame duration is needed to increase the reactivity of the system.

A wide variety of cell ranges up to 100 km is envisaged for future mobile systems [2]. Yet, in conventional TDD systems, the duration of the idle period required between a DL sub-frame and an UL sub-frame increases with respect to the targeted coverage of the BS, i.e., the cell size. Thus, a sub-frame duration that has been optimized for a typical cell radius of 1 km may become inappropriate for a very large cell size because of a too large idle period overhead.

In this paper, we investigate the dimensioning of the idle period required between a DL sub-frame and an UL sub-frame of a TDD mobile cellular system intended to be deployed in small micro-cells as well as in large macro-cells. Following the trend of current standardization bodies, we assume an OFDM-based transmission in the DL and a quasi-synchronous based transmission in the UL. We thus propose a UE-specific IP duration, which allows to significantly decrease the idle period overhead for large cells. We show that the proposed IP dimensioning does not require any specific signaling except the timing advance information already needed by UEs to align their UL sub-frames at the BS. The remaining of this paper is organized as follows: In section II, we introduce the reasons for idle period insertion in TDD communications and describe efficient solutions in block-wise transmission. In section III, we describe the cell-specific strategy that is commonly employed for dimensioning this idle period. Then, we detail our proposed solution based on a user-specific approach and provide an analysis of the expected gains in DL data-rates. Section IV provides numerical results for a TDD realistic scenario as envisaged for the long term evolution of third generation cellular networks [3]. Conclusions are drawn in section V.

II. IDLE PERIOD IN BLOCK-WISE TDD COMMUNICATIONS

A. Idle period requirements

As depicted in Fig. 1, a TDD frame is composed of DL and UL sub-frames. At a DL / UL switching point, i.e., when a DL sub-frame is followed by an UL sub-frame, an idle period IP_{DLUL} has to be reserved by the BS between the end of the DL sub-frame transmission and the beginning of reception of the following UL sub-frame transmitted from one or more UEs.

As depicted in Fig.1, IP_{DLUL} has to be larger than the sum T_{DLUL} of the round trip delay (twice the propagation delay T_{prop} from the BS to the UE) and the receive-to-transmit UE switching time T_{RTUE}:

$$IP_{DLUL} \geq T_{DLUL}=2T_{prop}+T_{RTUE} = 2d/c + T_{RTUE} \quad (1)$$

where d is the distance from the UE to the BS and c is the celerity of light.

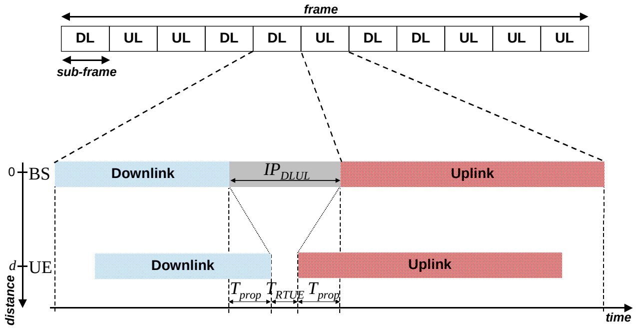

Figure 1: Idle period IP_{DLUL} between two consecutive DL and UL sub-frames.

From (1), the larger the distance d the longer T_{DLUL} and the shorter the effective transmission duration. In practice, T_{RTUE} has a few micro-second duration, e.g., 8 µs, which is negligible as compared to T_{prop} that reaches 100 µs for a UE located 30 km far from the BS.

No idle period is needed between two consecutive DL sub-frames in TDD. Similarly, when a UE is scheduled in consecutive UL sub-frames, there is no need for any idle period in between. However, if timing advance is not accurate enough, there may be a need for a short idle period to avoid overlapping of consecutive UL sub-frames transmitted from distinct UEs. In this case however, the transmitted signal properties, e.g., the cyclic prefix of block-wise transmission techniques, may alternatively be used to absorb the synchronization mismatch.

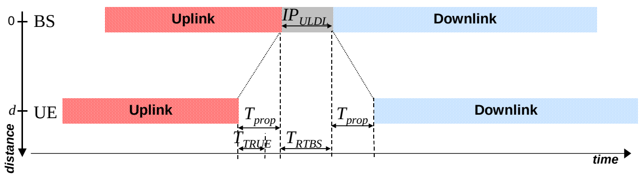

Figure 2: Idle period IP_{ULDL} between two consecutive UL and DL sub-frames.

Finally, a small idle period has also to be reserved by the BS between the end of the reception of an UL sub-frame and the beginning of transmission of the following DL sub-frame. As depicted in Fig. 2, the idle period during which the Node B is not active, referred to as IP_{ULDL}, has to be larger than the time T_{RTBS} for the BS to switch from receive to transmit mode. This idle period also depends on the UE switching time T_{TRUE} and the propagation delay T_{prop}:

$$IP_{ULDL} \geq \max\left(T_{TRUE} - 2T_{prop},\ T_{RTBS}\right) \tag{2}$$

As T_{prop} is increased, the impact of the UE switching time on T_{ULDL} is reduced. In reality, the system needs to cope with a range of T_{prop} values, including down to $T_{prop}\approx 0$, and so the time IP_{ULDL} must be set according to the maximum of the UE or BS switching times. These switching times are however expected to last a few micro-seconds.

In the sequel, we focus on the idle period IP_{DLUL} needed between a DL sub-frame and a following UL sub-frame.

B. *Idle period reservation in block-wise transmission*

When block-wise transmission is performed as in an OFDM transmission including cyclic prefix, the block structure of symbols can be taken into account for the dimensioning of idle periods. Indeed, by choosing the idle period as a multiple of symbol durations T_{SDL}, the DL/UL idle period duration can easily be adapted with respect to the cell size while keeping same transmission parameters (e.g., for an OFDM transmission, the sampling frequency, the Fast Fourier Transform dimension, the cyclic prefix, …) among sub-frames including or not an IP.

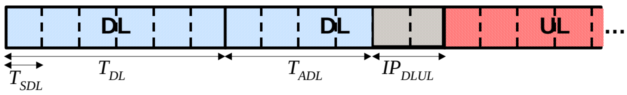

Figure 3: Idle period IP_{DLUL} reservation in a DL sub-frame using block-wise transmission.

As depicted in Fig. 3, the idle period IP_{DLUL} can be reserved from the end of the DL sub-frame. Compared to the original DL sub-frame duration composed of M symbol durations, the DL active transmission duration T_{ADL} is then reduced to M-$I(d)$ symbol durations where $I(d)$ is the number of idle symbols:

$$IP_{DLUL} = I(d)\,T_{SDL} = \left\lceil \left(2d/c + T_{RTUE}\right)/T_{SDL} \right\rceil T_{SDL} \tag{3}$$

Here, $\lceil x \rceil$ is the smallest integer larger than x.

When applying (3), the idle period duration IP_{DLUL} may be over-sized. However, provided that the symbol duration is not too large, the drawback of a slight over-dimensioning can be easily compensated by a benefit in flexibility. Furthermore, when the same communication system is intended to be deployed in paired bands with frequency division duplex (FDD) and unpaired bands with TDD, a maximum commonality between TDD and FDD systems is guaranteed, which offers to operators and manufacturers further business opportunities.

C. *Active transmission duration*

For given DL and UL traffics, the DL active transmission duration varies according to the repartition of DL and UL sub-frames in the frame and the corresponding need of idle periods.

Let N be the total number of sub-frames per frame, D being the number of DL sub-frames. Assuming that the first sub-frame of each frame is always reserved for DL in order to allow UE synchronization, the number X of DL/UL switching points per frame follows the following rule:

$$1 \leq X \leq \lfloor N/2 \rfloor - \lfloor |D - N/2| \rfloor \tag{4}$$

Here, $\lfloor x \rfloor$ is the largest integer smaller than x.

For a given percentage of DL sub-frames per frame, we may be interested in quantifying the *DL efficiency*, which is defined as the number of DL active symbols over the total number of DL symbols in the frame. If only one DL/UL switching point per frame is allowed, the DL efficiency is maximum and equal to $E_{\max}(d)$. On the opposite, to reduce the latency, the DL and UL sub-frames may be interleaved, which results in a minimum efficiency $E_{min}(d)$ since the number of switching points is maximized.

$$E_{\max}(d) = 1 - I(d)/(DM) \tag{5.a}$$

$$E_{\min}(d) = 1 - I(d)\left(\lfloor N/2 \rfloor - \lfloor |D - N/2| \rfloor\right)/(DM) \tag{5.b}$$

III. STRATEGIES FOR IDLE PERIOD DIMENSIONING

A. *Cell-specific idle period dimensioning*

The dimensioning of IP_{DLUL} is usually cell-specific, i.e., common to all UEs that are connected to a same BS, as in recent TDD standards such as TD-SCDMA, UMTS-TDD and IEEE802.16e. In this case, IP_{DLUL} has to be dimensioned according to the maximum cell coverage. The number of idle symbols in (3) is then given by:

$$I(d=R_0)=\left\lceil \left(2R_0/c+T_{RTUE}\right)/T_{SDL} \right\rceil \qquad (6)$$

Thus, assuming that T_{RTUE} is negligible, T_{DLUL} ranges from 33 µs for R_0 = 5 km to 667 µs for R_0 = 100 km. As a matter of fact, the active transmission duration, which is constant for all UEs in a same cell, decreases when R_0 increases. Fig. 4 depicts an example of such a cell-specific dimensioning with an original DL sub-frame duration of 0.5 ms. The sub-frame is composed of 7 symbols, 3 of which being idle to create the DL/UL idle period. Considering a switching time T_{RTUE}=8 µs and T_{SDL}=71.4 µs, the maximum cell range R_0 is 30.9 km.

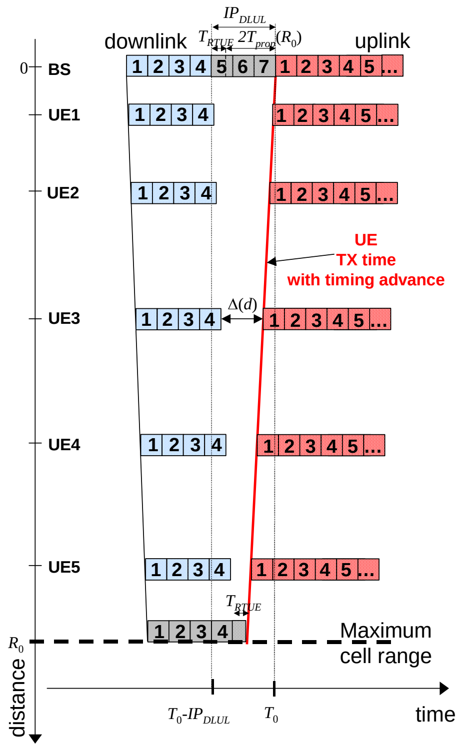

Figure 4: Cell-specific DL/UL idle period (R_0 = 30.9 km).

With this approach, the maximum and minimum DL efficiencies may be derived by incorporating (6) in (5.a) and (5b). For a radio frame including only one DL/UL switching point, the throughput loss induced by this IP dimensioning remains negligible. However, since a larger number of switching points may be desirable to reduce the network latency and benefit from channel reciprocity, the throughput loss might become prohibitive with such a rigid cell-specific dimensioning.

As shown in Fig. 4, the creation of the DL/UL idle period allows UEs to align their UL sub-frames at time T_0 at the BS by using timing advance mechanisms. In practice, thanks to an initial UL random access procedure, the BS is able to determine the UL transmission delay $\Delta(d)$ that has to be considered by each UE between the end of the reception of the DL symbols and the beginning of the transmission of the UL symbols, as:

$$\Delta(d)=IP_{DLUL}-2d/c \qquad (7)$$

This UE-specific information has to be transmitted regularly by the BS so as to follow each UE movement.

B. *User-specific idle period dimensioning*

As another more flexible approach, we propose to allow the DL/UL idle period to vary within the cell from one UE to another according to its distance *d* from the BS. Accordingly, the number $I(d)$ of idle symbols varies by strictly following (3). Indeed, even in a large cell, some UEs may be close to the BS. Transmission of additional symbols only for these close UEs is then possible. If an active UE is located at a distance $d<R_0$ from the BS, it can receive a number $N_A(d)$ of additional symbols as compared with the cell-specific approach, where $N_A(d)$ is given by:

$$N_A(d)=I(R_0)-\left\lceil \left(2d/c+T_{RTUE}\right)/T_{SDL} \right\rceil=\left\lfloor \left(\Delta(d)-T_{RTUE}\right)/T_{SDL} \right\rfloor \qquad (8)$$

Of course, this throughput gain can only be achieved if the traditional cell-specific approach requires more than one idle symbol, i.e., for a cell radius such that:

$$R_0>c\left(T_{SDL}-T_{RTUE}\right)/2 \qquad (9)$$

In this case, the maximum number of additional symbols that a BS is able to transmit is conditioned by the closest active UE of the cell.

Fig. 5 illustrates the proposed strategy with same parameters as used in Fig. 4. The *default* DL active transmission duration corresponds to 4 symbols durations which can be received by all UEs in the cell.

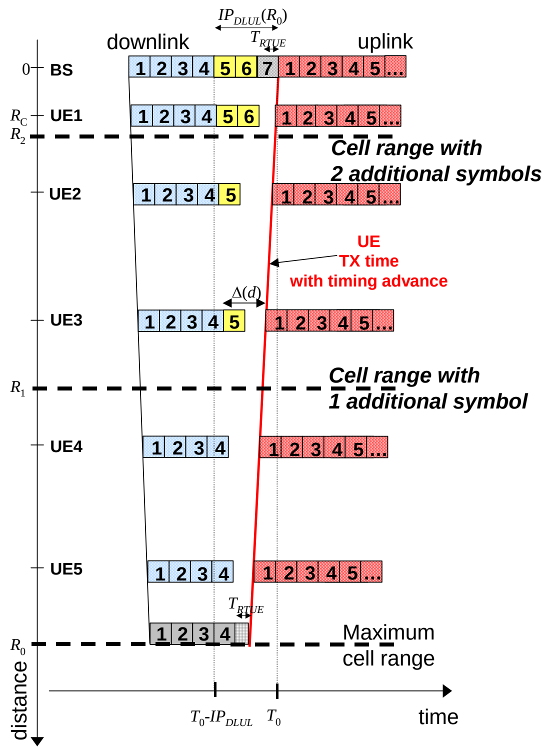

Figure 5: UE-specific DL/UL idle period (R_0 = 30.9 km).

For UE2 and UE3 at a distance smaller than R_1 = 20.2 km, an additional symbol can be received whilst still allowing timing alignment of all UL sub-frames at the BS. In contrast, for UE4 and UE5 that are farther, this additional symbol cannot be processed when it reaches them, as they are already transmitting to guarantee timing alignment at the BS. For UE1, at a distance smaller than R_2 = 9.5 km, two additional symbols can be processed. The intermediate cell radii R_i allowing the transmission of additional symbols are defined as:

$$R_i = c\left(\left(I(R_0)-i\right)T_{SDL} - T_{RTUE}\right)/2 \qquad (10)$$

As a result, the DL active transmission duration can be extended according to the minimum distance $d_{\min}$ between an active UE in the cell and the BS.

Moreover, assuming a constant transmit power for all symbols of the sub-frame, the supplementary symbols may carry higher modulation and coding schemes (MCS). Indeed, the large part of the energy spent during the default DL active transmission duration to reach far UEs can be reused during the transmission of the supplementary symbols for close UEs, which may thus benefit from an improved signal-to-noise ratio.

Besides, in Fig. 5, the BS is assumed to transmit the UE-specific timing advance information, which is, as in Fig. 4, the delay that has to be observed after the end of the reception of the default DL active transmission before beginning to transmit UL sub-frames. Thus, from (8), the number of additional symbols $N_A(d)$ to be considered by each UE at distance d can be easily derived from $\Delta(d)$ without any specific signaling.

We may assume that there always exists a UE that is very close to the BS in order to be able to benefit from a maximum number of additional symbols. In this case, this UE only requires one idle symbol between DL and UL sub-frames to allow for switching time between reception and transmission modes. Thus, the minimum and maximum DL frame efficiencies can be derived from (5.a) and (5.b) as:

$$\max_d\left(E_{\max}(d)\right) = 1 - 1/(DM) \qquad (11.a)$$

$$\max_d\left(E_{\min}(d)\right) = 1 - \left(\lfloor N/2 \rfloor - \lfloor |D - N/2| \rfloor\right)/(DM) \qquad (11.b)$$

In practice, the gain in active transmission duration is conditioned by the probability of having at least one UE able to detect additional symbols from the BS. Assuming a total number of N_U simultaneous active UEs that are uniformly distributed in the circular cell, this cumulative distribution function $\Pr(d \le R_i)$ is given by :

$$\Pr(d \le R_i) = 1 - \left(1 - \left(\frac{R_i}{R_0}\right)^2\right)^{N_U} \qquad (12)$$

From (5) and (12), we may thus derived the ratios of DL active symbols averaged over the UE distribution probability in the cell according to the various frame configurations, i.e.:

$$\mathrm{mean}\left(E_{\max}(d)\right) = 1 - \frac{1}{DM}\int_0^{R_0} I(\mu) f(\mu)\, d\mu \qquad (13.a)$$

$$\mathrm{mean}\left(E_{\min}(d)\right) = 1 - \frac{\left(\lfloor N/2 \rfloor - \lfloor |D - N/2| \rfloor\right)}{DM}\int_0^{R_0} I(\mu) f(\mu)\, d\mu \qquad (13.b)$$

with $\Pr(d \le d_0) = \int_0^{d_0} f(\mu)\, d\mu$

Finally, we may rewrite the continuous integration in (13) as :

$$\begin{aligned}\int_0^{R_0} I(\mu) f(\mu)\, d\mu &= \sum_{i=0}^{N_A(0)} \Pr\left(R_{i+1} < d \le R_i\right)\left(I(R_0) - N_A(R_i)\right) \\ &= I(R_0) - \sum_{i=0}^{N_A(0)} i\left(\Pr(d \le R_i) - \Pr(d \le R_{i+1})\right) \\ &= I(R_0) - \sum_{i=1}^{N_A(0)} \Pr(d \le R_i)\end{aligned} \qquad (14)$$

IV. NUMERICAL RESULTS

We evaluate the benefits of a UE-specific DL/UL IP for a DL OFDMA system as envisaged by the 3GPP study item group that deals with the long term evolution of UMTS [3, section 7.1.1].

The DL sub-frame is composed of 7 OFDM symbols, some of which may be idle when needed to fit the DL/UL idle period requirements. Each OFDM symbol with T_{SDL}=71.4 µs is shared by the different active UEs which are mapped on different subsets of sub-carriers. When an additional OFDM symbol is available thanks to UE-specific idle period dimensioning, we assume that it is fully used by the UEs which are capable of receiving it. Thus, the throughput gain is maximized.

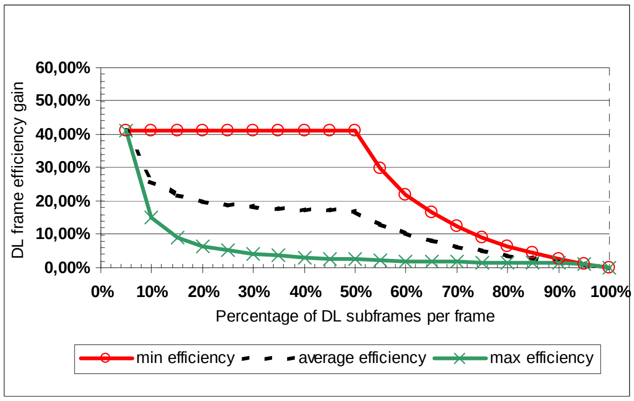

Figure 6: DL frame efficiency gain of UE-specific IP dimensioning (R_0=30km, N_U=10, parameters [3, section 7.1.1]).

For different percentages of DL sub-frames per frame, Fig. 6 represents the DL frame efficiency gain provided by the UE-specific IP dimensioning as defined in (13) compared to the cell-specific IP dimensioning as defined in (5) using (6). We assume N_U=10 active users which are uniformly distributed in a cell of R_0=30 km radius. In this case, the cell-specific IP consumes 3 OFDM symbols as idle symbols whereas up to 2 can be saved with the UE-specific IP. Thus, as depicted, there is always a gain by using a UE-specific IP. This gain decreases with the percentage of DL sub-frames as a result of a lower impact of the IP shortening when applied to a longer DL transmission duration. The curve referred to as “min efficiency curve” corresponds to a frame configuration with as many switching points as possible so as to reduce the network latency. In this case, the proposed method provides a gain of 41% over the traditional approach up to DL/UL symmetry.

There is still a gain of 22% with 60% of DL sub-frames. The curve referred to as “max frame efficiency” corresponds to frame configurations with a single switching point so at to maximize the frame efficiency. In this unfavorable case, the few opportunities to gain additional symbols with the UE-specific approach result in a small gain. By averaging over all possible number of switching points, a 17% gain is provided at DL/UL symmetry.

In Fig. 7, the DL frame efficiency gain is represented for N_U=10 active users within a cell radius of R_0=100 km, which is considered as a limit deployment scenario of future cellular systems [2]. Here, the cell-specific IP requires 10 idle OFDM symbols which is more than the content of one entire DL sub-frame. In this case, the base station is forced to aggregate DL sub-frames by groups of at least 2 sub-frames (double sub-frame) to allow switching points between DL and UL communications. In the figure, we also consider the transmission of DL sub-frames by groups of 3 (triple sub-frame) and 4 (quadruple sub-frame). This constraint limits the number of switching points, which reduces the IP overhead in the frame. However, this limits the flexibility in the frame configuration, increases the system latency, degrades the asymmetry granularity and reduces the benefit from channel reciprocity. Therefore, to minimize the network latency, the frame configuration that maximizes the number of switching points between DL and UL groups of sub-frames is considered.

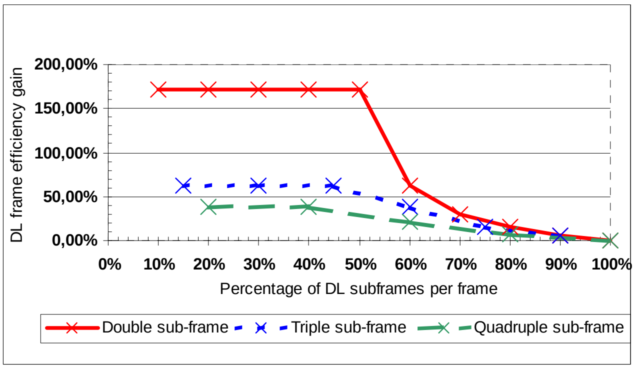

Figure 7: DL frame efficiency gain of UE-specific IP dimensioning (R_0=100km, N_U=10, parameters [3, section 7.1.1]).

For such a large cell, the gain provided by the UE-specific IP dimensioning reaches up to 170% when using double sub-frames. In other words, using the UE-specific IP dimensioning is the only way to allow transmission of DL sub-frames with a low latency without sacrificing too much the DL efficiency. Even if we limit the number of switching points by transmitting triple (resp. quadruple) sub-frames, a gain of 38% (resp. 21%) can be achieved with 60% of DL sub-frames per frame.

The influence of the active number of UEs per cell on the DL frame efficiency is depicted in Fig. 8 for different cell radii. A DL/UL symmetric traffic is assumed with maximization of the number of switching points to satisfy low latency constraints. The UE-specific IP dimensioning is compared to the cell-specific approach. First, the efficiency using a cell-specific IP is obviously independent on the number of UEs in the cell. This efficiency decreases with the cell radius from 71% for a 10 km radius down to 14% for a 60 km radius. Thus, the cell-specific approach is shown to be completely ineffective for a deployment in large cells. In contrast, the efficiency of the UE-specific approach varies according to the number of UEs in the cell. Indeed, the higher the number of UEs, the higher the probability that one UE is close to the BS, which can thus transmit additional symbols to it. For a 10 km cell radius, the maximum efficiency (corresponding to a single symbol IP duration) is achieved as soon as 3 UEs are active. For a 30 km cell radius, this maximum is achieved for a number of UEs larger than 30. For a very large radius of 60 km, this maximum efficiency can still be reached if 100 UEs are simultaneously active.

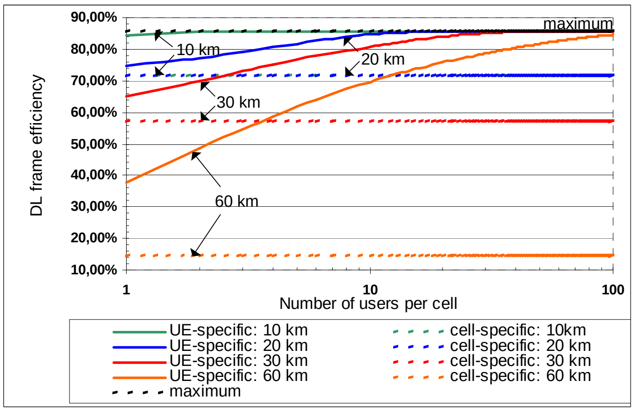

Figure 8: DL frame efficiency (*D*/*N*= 50%, parameters [3, section 7.1.1]).

V. Conclusion

In this paper, we propose to shorten the idle period that is needed between a DL sub-frame and a following UL sub-frame in a TDD communication system with synchronous or quasi-synchronous operation in UL. In contrast to a cell-specific idle period dimensioning, we show the benefits of a user-specific idle period dimensioning. With no specific signaling except the usual timing advance value which is regularly transmitted by the BS to each terminal, we demonstrate that it is possible to achieve low-latency high-efficiency TDD communications even for very large cells.

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