Energy Saving via Efficient Allocation of Paging Frames

Ahmad Awada and Diomidis S. Michalopoulos
Nokia Bell Labs, Munich, Germany
Email: {firstname.lastname}@nokia-bell-labs.com

***Abstract*—We propose an alternative design for paging in 5G networks, and investigate its potential for increasing the energy efficiency of base stations. The proposed design allocates the paging frames in certain radio frames, aiming at providing longer sleep opportunities to the base stations. This allows more hardware components to be deactivated and reduces the number of transitions between active and sleep mode, leading to lower energy consumption. The resulting energy saving is evaluated and compared with that of the reference paging scheme. Numerical results demonstrate that noteworthy energy savings are achieved for certain parameter configurations.**

***Index Terms*—Paging, discontinuous reception (DRX) cycle, energy efficiency.**

I. Introduction

Paging is a mechanism that mobile networks use to notify terminals about an incoming call, data message or updates on system information [1]. Paging typically involves the transmission of the paging message, which is then utilized by the User Equipments (UEs) for identifying whether there is a new transmission session to them.

Paging in cellular setups: In Long Term Evolution (LTE), the paging message is transmitted periodically to the UEs, in time instances known as Paging Occasions (POs), following certain repetition cycles [2]. For decoding the paging message, the UEs follow certain mechanisms which involve monitoring specific Radio Frames (RFs) that are termed Paging Frames (PFs). As a result, each UE knows if there is an incoming call or data transfer, by comparing the identities of the paged UEs, included in the paging message, with its own identity.

Energy saving opportunities: The power consumption of Base Stations (BSs) constitutes the highest portion of the total power consumption in mobile networks [3], [4]. More energy-efficient BSs would help mobile operators to reduce their operational costs and to operate the network in a more sustainable manner. From that perspective, energy saving is considered to be an integral part of upcoming fifth generation (5G) solutions and technologies [5].

Nevertheless, the existing paging process in LTE, as well as that in 3G systems, is not deemed energy efficient. As explained later in Section II, this is because the distribution of the PFs over time does not provide the network with long sleep opportunities. As a result, short sleep opportunities restrict the BSs from further reducing their energy consumption, since only a limited set of BS components can be deactivated.

Contribution and structure: As an attempt to achieve higher energy savings at BSs, we propose new alternative designs for the distribution of PFs. Such new designs provide longer sleep opportunities for the BSs, as well as less number of transitions between active and sleep mode.

The paper is organized as follows. First, we review the PF distribution in LTE, and describe two new alternative designs that can serve as potential candidates for 5G system. Then, we analyze the energy saving of the two new designs along with that of the LTE solution, treated here as the reference scheme. Numerical results are provided to benchmark the performance of the two new designs against the reference scheme.

II. New Designs for Paging Frame Distribution

In this section we review the PF distribution that is followed in LTE (c.f. Section II-B), and propose alternative designs that aim at larger energy saving in Sections II-C and II-D. An illustrative view of the allocation of PFs to the monitoring UEs is then provided in Section II-E.

A. Main Assumptions and Definitions

For all considered schemes, it is assumed that the POs within PF can be time- or frequency-division multiplexed with the Synchronization Signal Blocks (SSBs) [6]. The network is assumed to remain active during the entire PF, as well as during the RFs carrying the SSBs. The network has the opportunity to enter in sleep mode in the remaining RFs of the Discontinuous Reception (DRX) cycle, provided that no UE is scheduled for data transmission.

The following definitions are used throughout the paper.

1) The DRX cycle duration of UE is denoted by T, i.e., the duration of the repetitive process where the paging messages are sent. Following the typical notation used in LTE standards [1], T is normalized to the number of RFs included within one DRX cycle. A typical value of T is 32 radio frames per DRX cycle. An exemplary illustration of the DRX cycle is shown in Fig. 1.
2) The number of POs per DRX cycle is denoted by nB, which is expressed in terms of T. Typically, nB ranges from $T/32$ to $4T$, i.e., from 1 to 128 POs within one DRX cycle T of 32 RFs. [1]. In the example of Fig. 1, $nB = T/2$.
3) The PF is a RF in which one or multiple POs are transmitted. The length of one RF is given by T_{RF}. The PFs are marked with shaded color in Fig. 1.

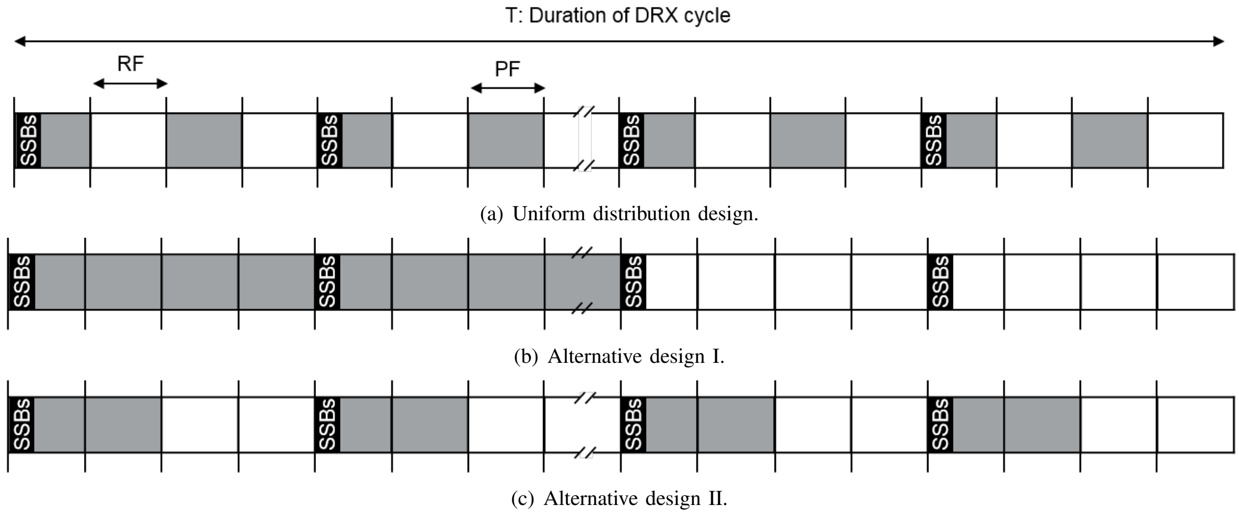


Fig. 1. Locations of PFs in LTE reference scheme (uniform distribution), and alternative designs I and II for $nB = T/2$ and SSB periodicity P of four RFs.

4) The UE synchronizes to the 5G network using SSBs that are transmitted periodically. The periodicity of SSBs is given by P in terms of RFs and is configured by the network. Typically, P takes values in the interval from 0.5 RFs to 16 RFs, i.e., its duration ranges from 5 ms to 160 ms [6] for $T_{RF} = 10$ ms.

B. Uniform Distribution of PFs (Reference Scheme)

Here we study the LTE paging design, which is used as reference scheme. In LTE, PFs are uniformly distributed over a DRX cycle. The UEs are first assigned a so-called UE identity number, UE_{ID}. For obtaining a uniform mapping of UE_{ID} across the UEs, the modulo process is used in conjunction with the International Mobile Subscriber Identity (IMSI) number, i.e., $UE_{ID} = IMSI \bmod 1024$ [2]. The PF monitored by UEs having the same UE_{ID} is given by so-called System Frame Number (SFN) satisfying

$$SFN \bmod T = T/N \cdot (UE_{ID} \bmod N), \qquad (1)$$

where N is the number of PFs in a DRX cycle [2], i.e., $N = \min(T, nB)$.

The uniform distribution of PFs is depicted in Fig. 1(a), for the case where every second RF is a PF (i.e., for $nB = T/2$). In this example, there are $T/2$ sleep opportunities that are spread over the DRX cycle, each with a duration of one RF.

C. Alternative Design I

Alternative design I schedules all PFs of a DRX cycle at the beginning of the cycle. This design provides the network with the opportunity to sleep in all RFs located between consecutive SSBs. Similarly as in (1), the PF monitored by UEs having the same UE_{ID} is given by the SFN satisfying

$$SFN \bmod T = UE_{ID} \bmod N. \qquad (2)$$

Fig. 1(b) shows the distribution of PFs for alternative design I with $nB = T/2$ and SSB periodicity P of four RFs. In this case, the first half of RFs in each DRX cycle are used as PFs. As a result, there are $T/8$ sleep opportunities that are occurring in the second half of RFs in a DRX cycle, each with a duration of three RFs. It is noted that, compared to the reference scheme, the duration of each sleep opportunity has increased threefold; however, the total number of sleep opportunities in a DRX cycle suffered a fourfold decrease.

D. Alternative Design II

In alternative design II, the PFs are consolidated uniformly after each SSB. The motivation for this scheme is that the network has to become active anyway during the RFs containing the SSBs, hence sending the paging message in such RFs would not limit the sleep opportunities. As such, the network enters in sleep mode in the remaining non-PFs located between consecutive SSBs. Similarly as in (1), (2), the PF monitored by UEs having the same UE_{ID} is given by the SFN satisfying

$$SFN \bmod T = T/N' \cdot (UE'_{ID} \bmod N') + \lfloor UE'_{ID}/N' \rfloor, \qquad (3)$$

where $UE'_{ID} = UE_{ID} \bmod N$ and $N' = \min(T, T/P)$.

Fig. 1(c) illustrates the PF distribution in alternative design II for the same assumptions as Figs. 1(a) and 1(b). Herein, there are $T/4$ sleep opportunities that are spread over DRX cycle, each with a duration of two RFs. In fact, considering the advantages and drawbacks of the schemes mentioned above, alternative design II represents a compromise solution between the reference uniform distribution and design I.

E. Illustrating the Paging Frames Monitored by UEs

The paging frame designs described above correspond to different mappings of PFs to the identity number of UEs, UE_{ID}. Such mappings are illustrated in Fig. 2, which shows the index of monitored PF as a function of UE_{ID} for the LTE reference scheme (uniform) and alternative designs I and II, computed using (1), (2) and (3), respectively. For clarity, the index of monitored PF is shown only for the first 20 possible

TABLE I
THE DEPTH AND NUMBER OF SLEEP OPPORTUNITIES WITHIN A DRX CYCLE FOR THE THREE DESIGNS AND $nB < T$.

Case		**Uniform design**	**Design I**	**Design II**
$nB \le T/P$	τ_1	$(P-1)\cdot T_{RF}$	$(P-1)\cdot T_{RF}$	$(P-1)\cdot T_{RF}$
	N_1	T/P	$(T/P) - \lceil nB/P \rceil$	T/P
	τ_2	$-$	$\max(0, P - \max(nB,1))\cdot T_{RF}$	$-$
	N_2	$-$	1	$-$
$nB > T/P$	τ_1	$(T/nB - 1)\cdot T_{RF}$	$(P-1)\cdot T_{RF}$	$(P - (nB \cdot P)/T)\cdot T_{RF}$
	N_1	nB	$(T/P) - \lceil nB/P \rceil$	T/P
	τ_2	$-$	$\max(0, P - \max(nB,1))\cdot T_{RF}$	$-$
	N_2	$-$	1	$-$

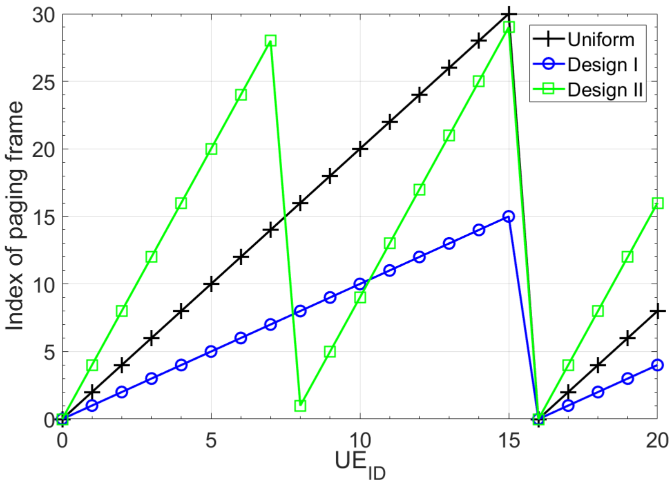


Fig. 2. The index of monitored PF as a function of UE_{ID} for the LTE reference scheme (uniform) and two alternative designs I and II given for T = 32 RFs, $nB = T/2$ and SSB periodicity of four RFs.

values of UE_{ID} out of 1024, as the remaining ones follow the same recurring PF monitoring pattern. That is, as shown in Fig. 2, the first repetition starts at UE_{ID} = 16.

In Fig. 2, the parameters T = 32 RFs, $nB = T/2$ and SSB periodicity of four RFs were used as an example, corresponding to 16 PFs within a DRX cycle duration of 32 RFs. For the reference scheme, the indices of monitored PFs are 0, 2, . . ., 30, which are *uniformly* distributed over the DRX cycle duration of 32 RFs. In contrast, for design I the indices of monitored PFs are 0, 1, . . ., 15, i.e., they correspond to the first 16 *consecutive* RFs of the DRX cycle. As for design II, the indices of monitored PFs correspond to 0, 1, 4, 5, . . ., 28, 29. It is noted that for design II such indices are neither uniformly distributed nor strictly consecutive.

III. ENERGY SAVINGS

Next, we evaluate the energy savings of the three considered schemes with respect to the energy consumed in the idle mode. That is, the energy consumed by the BSs for the case where there is zero load served by the system, implying that the power amplifier is active but not transmitting [7].

As highlighted in [4], the deactivation and activation of the BS hardware components is non-ideal in practice, in the sense that some non-zero time is spent until the BS goes into and out of the sleep mode. We denote by S_D and S_A the deactivation and activation time, corresponding to the transition time from idle to sleep mode, and sleep to idle mode, respectively.

1) General Formula for Energy Savings: Let τ denote the total sleep depth duration of each sleep opportunity that includes, besides the actual sleep time, the deactivation and activation times. For instance, with reference to Fig. 1, the sleep depth τ is equal to 1, 3 and 2 RFs in Fig. 1(a), Fig. 1(b) and Fig. 1(c), respectively. Given a sleep opportunity with a depth τ within DRX cycle, the energy saving with respect to the idle mode, $E(\tau)$, can be computed as

$$E(\tau) = (P_{ID} - P_{SL}(\tau))\tau - \bar{P}_{SD}(\tau)S_D - \bar{P}_{SA}(\tau)S_A, \quad (4)$$

where P_{ID} denotes the BS power consumption in idle mode; $\bar{P}_{SD}(\tau)$, $\bar{P}_{SA}(\tau)$ are the average power consumption during the deactivation and activation phase of BS components, defined in [4, Eq.(4)] and [4, Eq.(3)], respectively as

$$\bar{P}_{SA}(\tau) = \beta_1(2P_{ID} - P_{SL}(\tau)), \quad (5)$$

$$\bar{P}_{SD}(\tau) = \frac{\beta_2}{2}\left(P_{ID} + P_{SL}(\tau)\right), \quad (6)$$

with β_1 and β_2 being system defined parameters [4]. $P_{SL}(\tau)$ is the power consumption during sleep time, and is approximated in [4] by an exponentially decaying function of τ, i.e.,

$$P_{SL}(\tau) = P_0 + P_m \exp\left(\left(-\omega_1 \log_{10}(\tau \cdot 10^6)\right)^{\frac{1}{\omega_2}}\right), \quad (7)$$

where P_m and P_0 are the power consumption at the first and fourth sleep level [4, Table I]; ω_1 and ω_2 are constants derived via a curve fitting process, and provided in [4, Table II] for various BS types.

In the following, we utilize (4) to derive the energy saving of the considered paging designs within a DRX cycle for $nB < T$. It is noted that, for the extreme cases of $nB \ge T$, all RFs within a DRX cycle are PFs. Consequently, following our assumption that the network remains active during the entire PF, no energy saving can be achieved.

2) Uniform Distribution of PFs (Reference Scheme): The energy saving, E_{DRX}, of the uniform distribution design within a DRX cycle, is computed as follows

$$E_{DRX} = N_1 E(\tau_1), \quad (8)$$

where N_1 is the number of sleep opportunities within a DRX cycle T, each with a sleep depth of τ_1. The formulas of N_1

and τ_1 are provided in Table I for the following two cases: 1) $nB \leq T/P$, which corresponds to the case when the number of POs in a DRX cycle is less or equal to the number of SSBs; 2) $nB > T/P$, which occurs when the number of POs in a DRX cycle is greater than the number of SSBs.

3) Alternative Design I: In contrast to the reference design, the sleep depth in alternative design I is not necessarily the same for all sleep opportunities within a DRX cycle. For instance, consider the case when $nB = T/16$, $P = 4$ and $T = 32$ RFs. Herein, there are $N_1 = 7$ sleep opportunities with a sleep depth τ_1 of 3 RFs, and $N_2 = 1$ sleep opportunity with a sleep depth τ_2 of 2 RFs within a DRX cycle (c.f. Table I). Considering the above, the energy saving E_{DRX} of the alternative design I within a DRX cycle is computed as follows

$$E_{DRX} = N_1 E(\tau_1) + N_2 E(\tau_2). \tag{9}$$

4) Alternative Design II: The energy saving of alternative design II is computed using the same Eq. (8) applied for uniform distribution design, yet with different parameters (c.f. Table I). It is noted that the sleep depth τ_1 and the number N_1 of sleep opportunities are the same in both designs for $nB \leq T/P$. This implies that alternative design II has the same energy saving as the uniform distribution design when the number of POs is less or equal to the number of SSBs within a DRX cycle. This is an expected observation, since for that case the energy saving is determined by the SSBs, rather than the PFs.

IV. Numerical Results

In this section, we provide numerical examples pertaining to the energy savings of the three considered schemes, E_{DRX}, based on the analysis of Section III.

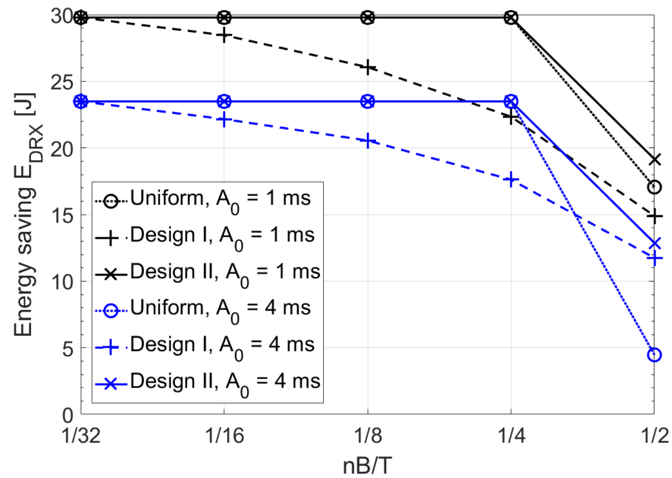
A. Configuration Parameters

The following configuration parameters are used: The BSs involved are assumed to correspond to 4x4 macro cells. This implies that, with reference to (7), the transmission powers at the first and fourth sleep level equal to $P_m = 86.3$ W and $P_0 = 6.16$ W, respectively; the transmission power in idle mode equals $P_{ID} = 139$ W [8]. The curve fitting parameters in (7) are adopted from [4], i.e., $\omega_1 = 0.38$ and $\omega_2 = 0.1350$, and the system defined parameters β_1 and β_2 equal unity [4].

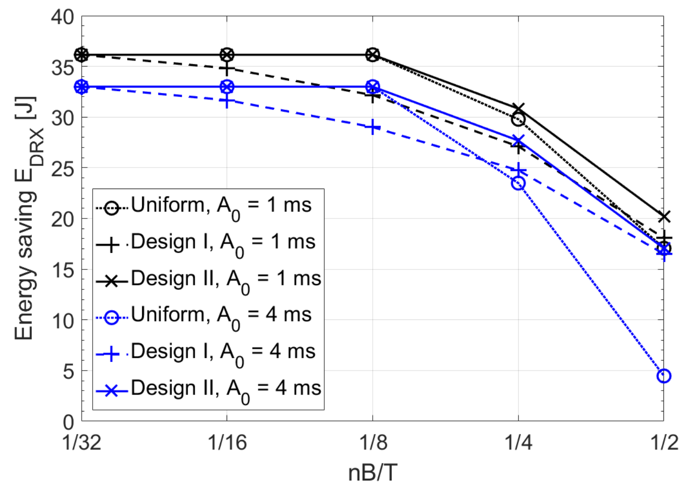
We adopt the typical duration of RF, such that $T_{RF} = 10$ ms, while the DRX cycle equals $T = 32$ RFs. As for the deactivation and activation time, S_D, S_A, the following configuration is used. We denote by $A_0 = S_D + S_A$ and $\eta = S_A/S_D$ the corresponding sum and ratio parameters, respectively, and use these parameters in Figs. 3 and 4. This facilitates obtaining insights of their composite effect on the overall performance, as explained below.

B. Performance Comparison

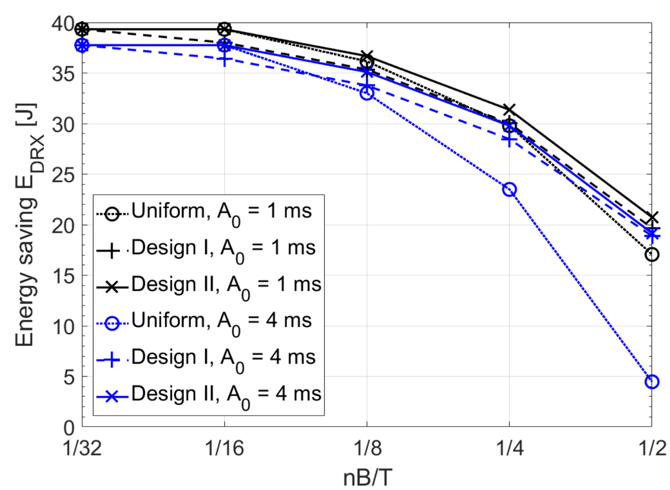
Fig. 3 illustrates the energy saving E_{DRX} as a function of the number nB/T of POs per RF, for $\eta = 20$ and varying values of A_0. The results correspond to SSB periodicity of $P \geq 4$ RFs (40 ms), since for smaller values of P, e.g.,



(a) SSB periodicity P of 4 RFs (40 ms).



(b) SSB periodicity P of 8 RFs (80 ms).



(c) SSB periodicity P of 16 RFs (160 ms).

Fig. 3. Energy saving E_{DRX} as a function of the number nB/T of POs per RF for the three designs with the SSB periodicity P and A_0 as parameters.

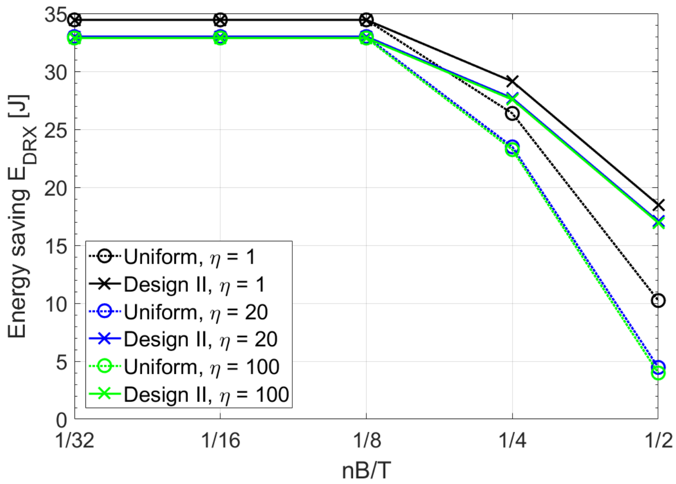


Fig. 4. Energy saving E_{DRX} as a function of the number nB/T of POs per RF for uniform scheme and design II with η as a parameter.

$P = 1, 2$ RFs, the SSBs dominate the energy consumption, leaving thus little room for energy savings with respect to the reference scheme. Nonetheless, it is observed that for $P \geq 4$ RFs alternative design II yields a considerable energy saving gain with respect to both the reference scheme and alternative design I. Such energy saving gain increases with the number of POs per DRX cycle, nB/T, as well as with the SSB periodicity, P. Interestingly, the performance of design I can be inferior to that of uniform design as the PFs are not necessarily multiplexed with RFs carrying SSBs.

Effect of parameter A_0: As expected, the sum of activation and deactivation times, A_0, has a large impact on the energy savings, since the savings due to sleep mode are counterbalanced by the large transition times to and from the sleep mode. The energy savings decrease for higher A_0 and this effect is more visible for smaller values of the SSB periodicity. It is also noted that alternative design II yields higher energy savings than the reference uniform design only when $nB > T/P$.

Effect of parameter η: We now focus only on the uniform (reference) scheme and alternative design II, and examine the impact of imbalanced activation and deactivation time on energy saving. Note that in practice S_A is usually larger than S_D, due to the larger process that a power amplifier activation entails [4]. Fig. 4 depicts the energy saving E_{DRX} for varying values of $\eta = S_A/S_D$. The sum $S_A + S_D$ is kept constant and equal to $A_0 = 4$ ms, while the assumed SSB periodicity is $P = 8$ RFs (80 ms).

As can be seen, larger values of η reduce the energy saving of each design, despite the fact that the total transition time is unaffected. However, the reduction in energy saving is larger in uniform design since, compared to design II, it yields a higher number of transitions between active and sleep mode. Nevertheless, we observe that such reduction saturates for large values of η, since for these cases the impact of the non-ideal transition time is dominated by the activation time.

V. Conclusion

Numerical results have shown that consolidating the PFs uniformly after each SSB (c.f. alternative design II) leads always to equal or higher energy saving than the LTE reference scheme, i.e., the uniform distribution of PFs in DRX cycle. Moreover, alternative design II provides more flexibility in user data scheduling between PFs, unlike design I where the PFs are consolidated consecutively at the beginning of each DRX cycle. As a result, alternative design II appears as an energy efficient solution for PF distribution in 5G cellular networks and beyond.

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