Split PO for Paging in B5G Networks

Mamta Agiwal[a], Anil Agiwal[b], Mukesh Kumar Maheshwari*[c], Shapna Muralidharan[d]

[a]*Sejong University, Seoul, South Korea*
[b]*Samsung Research, Seoul, South Korea*
[c]*Bahria University, Karachi, Pakistan*
[d]*Korea Institute of Science and Technology, Seoul, South Korea*

Abstract

Beyond 5G (B5G) wireless networks, imbued with several beams to support high-frequency spectrum, would require enhancements to the current paging monitoring mechanism in Idle mode Discontinuous Reception (IDRX) for improving UE's energy efficiency. The lengthy pre-wakeup and processing overheads in directional IDRX for beam tracking and time-frequency synchronization in every IDRX cycle would result in higher UE's power consumption. Recently, the functioning of Synchronization Signal Block (SSB) has been standardised for synchronization in New Radio (NR) 5G communications. In this article we first highlight inevitability and details of SSB measurements in every IDRX cycle of directional 5G/B5G communication. The UE's power saving reduces substantially due to SSB measurements as the deep sleep duration in every IDRX cycle shrinks. Moreover, during the time gap between periodic SSB transmission(s), the UE can only transit to light sleep. An early indication that can inform UE whether to measure multiple SSB's when paging is expected in an IDRX cycle or continue to deep sleep in absence of paging would be very beneficial in UE's power saving. We propose a novel Split PO Paging (SPOP) mechanism that manifests early indication, avoids unnecessary SSB measurements and reduces UE's pre-wakeup energy overheads. We use Markov chain modeling to analyze SPOP and validate our modeling through simulations. The Proposed SPOP can save more than 40% power compared to IDRX mechanism with elaborate pre wake-up and processing.

Keywords: Idle-DRX (IDRX), Paging, Power Saving, B5G

---

1. Introduction

The Beyond 5G (B5G) wireless networks would not only provide high data rate connectivity to people, things, machines, and industries but would also enhance the access efficiency in terms of agility, reliability, and energy efficiency. One of the key features to expect in 6G networks is the $10-100$ times improvement of UE's overall energy efficiency compared to 5G [1]. The 3rd Generation Partnership Project (3GPP) standardization body is also discussing enhancements to the Idle mode Discontinuous Reception (IDRX) mechanism in beam-based directional communication for improving UE's power saving [2]. In IDRX mode, UE manifests deep sleep for power saving and wakes up only in a Paging Occasion (PO) to monitor the Physical Downlink Control Channel (PDCCH) for paging. PDCCH for paging indicates Physical Downlink Shared Channel (PDSCH) resources for the paging message [3]. If the PDCCH for paging is received, UE performs PDSCH decoding in the PO. As beam based directional communication becomes essential with Gigahertz (GHz) and Terahertz (THz) frequencies in B5G networks [4, 5], the paging monitoring becomes much more challenging. The Synchronization Signal Block (SSB) measurements should precede every PO so that the UE can identify the beam to receive paging. Moreover, more than one SSB measurement may be required in each IDRX cycle for the reasons detailed ahead in the paper. Recently, the 5G New Radio (NR) has standardized the functioning of SSBs for directional communication such that they are periodically transmitted [6]. SSB measurements along with the time gap between SSB transmission(s) and PO would reduce deep sleep duration in each IDRX cycle. Thus, while the IDRX in legacy LTE/LTE-A networks gave UE's longer opportunity for deep sleep, IDRX in 5G and B5G networks results in reduced deep sleep duration due to the inevitable SSB measurements as shown in Figure 1. It is notable in Figure 1 that the UE can only transit to light sleep in between SSB transmission(s) and PO. More power consumption in every IDRX cycle would in turn reduce UE's battery life substantially. From the devices' usability point of view, improving battery life is one of most perennial challenges [7]. A survey by Qualcomm revealed that 60% of the consumers' consider battery life time performance as they key attributes that needs to be improved [8]. In this article we propose a novel mechanism to improve UE's power saving in IDRX mechanism by manifesting longer deep sleep through an early indication of paging arrival. The proposal also improves UE's battery life.

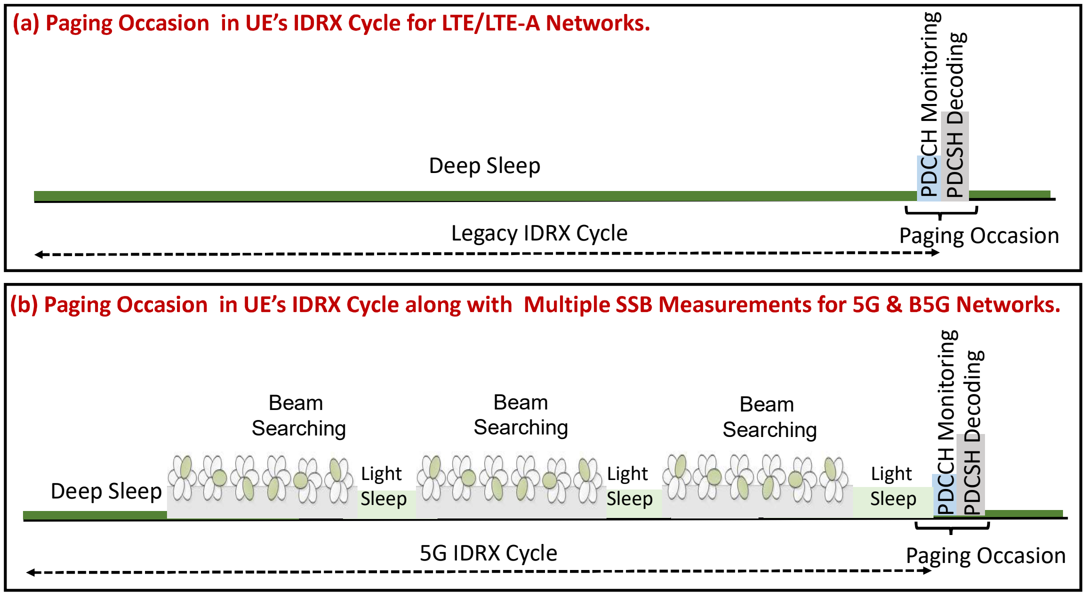


Figure 1: IDRX in LTE and 5G-NR Networks

Even though UE is required to periodically wake up for traffic monitoring in IDRX cycle, it is not necessarily paged in every PO as the wireless traffic is sporadic. It is to be noted that the wake up time is substantially high in B5G and many a times without any consequence. Thus, an early indication that enables UE to decide whether to wake up for elaborate SSB measurements or continue to sleep if there is no paging would be very beneficial in power saving. An early indication on absence of paging would allow the UE to avoid unnecessary long pre-wakeup. On the hand, UE would perform elaborate SSB measurements only when paging is indicated. In this article, we propose a novel concept called Split PO Paging (SPOP) that manifests early paging indication in B5G. More precisely, the main contributions are as follows:

1. We propose novel SPOP mechanism that uses PDCCH monitoring as an early indication based on which SSB measurements are avoided when paging indication is absent.

2. To manifest early indication, the paging occasion is split into two sub-occasions: (i) Paging Sub-Occasion 1 (PSO-1), where UE monitors the PDCCH for paging and (ii) Paging Sub-Occasion 2 (PSO-2), where UE

decodes PDSCH. Thus, PDCCH in PSO-1 can acts as an early indication in addition to scheduling PDSCH resources. In SPOP, we also consider appropriate time interval between PSO-1 and PSO-2 which should enable additional SSB measurements before PDSCH decoding if PDCCH for paging is received in PSO-1.

3. Power saving in SPOP would depend on the probability of paging arrival while monitoring PDCCH. Therefore, we apply Markov chain modeling to probabilistically evaluate the power saving in SPOP. We evaluate UE's transition probabilities to various states based on the arrival of the paging message. Subsequently, using holding times of different states, we evaluate power consumption and UE's battery life.

4. We show that the proposed SPOP can save twice and more power compared to the existing system that works without any early paging indication. Finally, we also validate our modeling through intensive simulations.

The rest of the paper is organized as follows. In the second section, we present the background on IDRX mechanism and its modification with respect to SSB measurements for 5G/B5G networks. Related work is also presented in this section. The third section presents a novel split PO paging mechanism and its analysis. The performance evaluation with respect to current system is presented in the subsequent section four. Section four also delineates the simulation results. Finally, section five presents the conclusion.

2. PRELIMINARIES

2.1. ***A. SSB Measurements in Directional Air Interface***

3GPP has standardized 'SS Block' (SSBs) for the new radio 5G communications in [9]. Unlike LTE, in 5G, the synchronization signals (Primary Synchronization Signal (PSS) and Secondary Synchronization Signal (SSS)) along with Physical Broadcast Channel (PBCH) are all packed as a single block. Jointly they are called as NR SS Blocks (SSBs). To support beam sweeping for SSB transmission, a new concept, SS burst set, is also introduced in NR [10]. Multiple consecutive SSBs together form an SSB Burst Set [6]. The default time setting for SSB burst set transmission is 20 ms [6][9]. This new concept facilitate beam alignment in directional communication at high frequencies by changing beam direction for each SSB transmission within the burst set as shown in Figure 2. It is notable that the spatial coverage of each beam is different. Each SSB in the SSB burst set has a unique number called SSB index by which it can be identified. UE measures the signal strength of SSBs and can identify the SSB index for the one with the strongest signal strength. As an example it is SSB index three in the Figure 2. Thus, the beam direction that provides strongest link between the UE and the gNB (5G base station) becomes known. This beam alignment between UE and gNB precedes any information exchange between UE and gNB. As directional interface is inevitable at high frequencies in B5G networks, IDRX for UE's power saving shall also incorporate the changes due to inclusion of SSB measurements in each of its cycle as explained in the subsequent subsection.

2.2. ***B. IDRX Novelty in*** 5***G and B***5***G***

IDRX is a popular mechanism in legacy networks to conserve UE's power. In IDRX cycle, the UE transits to a deep sleep mode and wakes up only for a specific sub-frame called the Paging Occasion (PO) to check paging as shown in Figure 1. Paging facilities in directing an incoming call to a UE that is in idle mode. In PO, UE first monitors the PDCCH for paging. It decodes PDSCH to receive the paging message only if the PDCCH for paging is received. However, if UE is not paged, it goes back to sleeps till the next PO. The UE monitors only one PO in every IDRX cycle. As IDRX allows long deep sleep with occasional waking up, it resulted in substantial power saving at UE in the legacy network. However, due to SSB measurements the IDRX cycle becomes complicated in directional air interface expected in 5G and B5G networks. The UE should first perform beam alignment by measuring SSBs in the SSB burst set to receive PDCCH for paging. Kindly note that these SSB measurements are to be performed in every IDRX cycle. During the duration between SSB measurement(s) and PO, the UE cannot transit to deep sleep as the transition energy is high. Furthermore, according to recent 3GPP discussion, multiple SSB measurements are required in each IDRX cycle [11]. This reduces the overall deep sleep time of UE as shown in Figure 1 since the IDRX cycle is imbued with several light sleeps and SSB measurements. As the number of beams increase with the increase in carrier frequency for wireless communication, the power consumption in IDRX cycle would further increase as shown in Figure 3. In Figure 3, we consider three SSB measurements per IDRX cycle. The intermediate light sleep is also considered. The details and parameters for the analysis are given in the subsequent sections. Figure 3 clearly shows that the power consumption

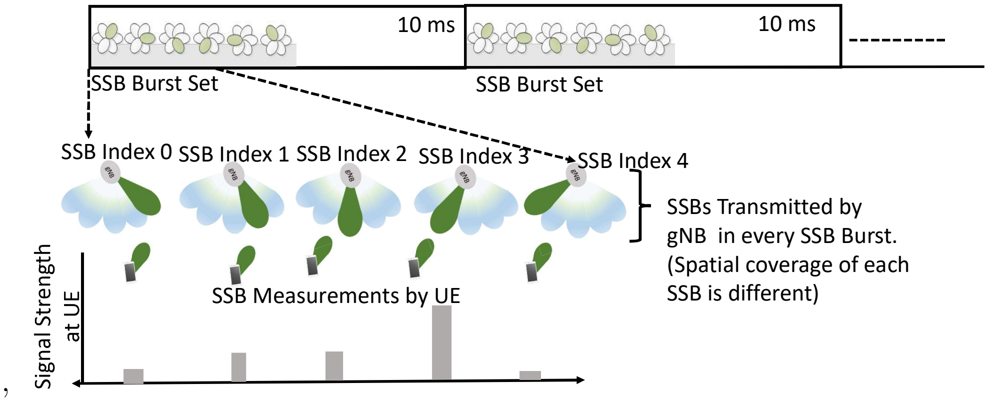


Figure 2: SSB Transmission and Beam Alignment.

in IDRX cycle of 5G and B5G is substantially higher than the legacy LTE networks and keeps increasing with the increase in number of beams. Thus, motivated, we propose a novel SPOP mechanism that can improve UE's power saving in 5G and B5G networks.

2.3. C. Related Work

Wireless networks forms one of the largest share of the Information and Communication technology (ICT) today while also supporting various other industries [12]. These industries are expected to further benefit from developments in 5G and B5G communications. The progress of 5G NR, specified by 3GPP, has presented several novel opportunities and prospects for the mobile communications ecosystem [13]. However, this progress has not been matched by developments in power saving technologies especially at the UE. There are some works on power saving at the network in view of ultra dense and massive base station connectivity expected in future 5G/B5G communications [14, 15, 16, 17]. These works evaluate: energy efficiency in 5G networks while considering Cloud-RAN [14], dynamic energy consumption control by power-off/on procedure on base stations using graph-theory [16], base station selection optimization [15] and green cloudlet network [17]. In particular, the 5G and B5G networks are considering computationally intensive techniques like larger transmission bandwidths, advanced coding techniques, higher modulation orders and sophisticated multi-antenna schemes [18]. These in turn would result in higher energy consumption and quickly depleting battery power, which already is one of the main dissatisfaction area for the users [8]. Thus, it becomes crucial to consider novel power saving techniques from the UE point of view. The second release of 3GPP's NR standards completed in the year 2020 discussed methods for UE's power saving in connected mode, such as power saving signal for discontinuous reception, secondary cell dormancy, cross-slot scheduling, etc [19, 20]. Several of these methods have been surveyed in [20]. From several such techniques under consideration, in particular, we would like to highlight the wake-up signaling. Wake-up signal indication (WUS) is a power saving identifier that is introduced in Release 16 for power saving in a connected mode DRX. The UE periodically monitors a narrow-band WUS at specific time instant, which indicates UE whether to process the upcoming PDCCH or remain in sleep mode [21]. Authors in [22] have presented a wake-up scheduling concept. First offline modeling and optimizing of the wake-up scheduler parameters is done for Poisson traffic. Then, the online optimization of the wake-up scheduler is presented that could be used for any traffic distribution. DRX mechanism without and with wake-up indication is simulated in [20]. For the traffic model in connected mode DRX 'OnDuration' timer and 'Inactivity' timer are considered in ms. It is observed that wake-up indication introduced in Release 16 for connected mode DRX can reduce $9\% - 33\%$ power consumption compared with the DRX operation in Release 15. The work in [23] also achieves higher relative power saving and reduced wake-up delay than the existing mechanism. A three-state semi-Markov DRX model is considered with adjustable DRX cycle and novel monitoring. Pre-grant message (PGM), a narrow-band control plane signaling method is introduced in [7] to improve the energy efficiency of the UE. The work particularly highlights effect on DRX with different traffic scenarios with latency constraints, like, FTP traffic, video streaming and VoIP. While considering UEs capacity, the power consumption at the base station is optimized in [24]. In [24], from perspective of the UE, objectives like handover, signaling bits, availability and power consumption linked to the data traffic are considered. Most of these works however, are based on connected mode DRX (CDRX). Kindly note that in connected mode DRX (CDRX), UE is connected to a specific gNB and performs frequent PDCCH monitoring. On the other hand UE is connected at the Mobility Management Entity (MME) level in IDRX and can be located in a wider tracking area. In IDRX, UE transits to longer deep sleep for more power saving as traffic activity is expected to be less. While in CDRX the inactivity timer is of prime importance, the paging arrival rate and number of UEs in a tracking area affect the power saving in an

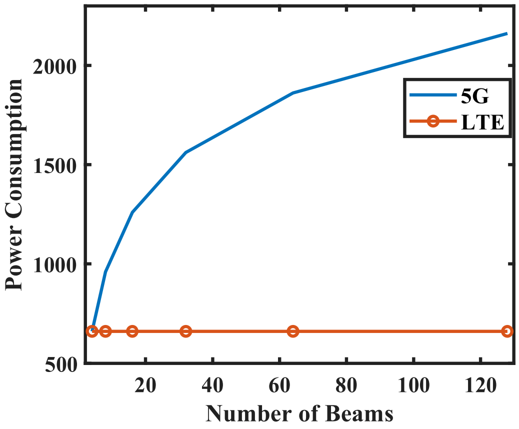


Figure 3: Comparison of Power Consumption in LTE/LTE-A and 5G/B5G wireless systems with Varying Number of Beams

IDRX mechanism. To the best of our knowledge analysis of IDRX in B5G and early paging indication applied to IDRX mode is limited in the existing literature. More recently, 3GPP Release 17 scheduled for 2022 has placed focus on UE's power saving enhancements in idle mode as well [25]. In [26], the difference in default IDRX cycle length and UE negotiated cycle length are manipulated to achieve power saving in B5G networks. Two types of PO monitoring are considered (i) both paging message and short message monitoring in one type of PO and (ii) only short message monitoring in the second type of PO so that System Information (SI) updates and emergency notifications are not missed when UE negotiated cycle is considered [26]. In this article, we propose a novel paging monitoring concept, Split PO paging (SPOP), for the idle mode DRX (IDRX) mechanism that is different from the work in [26]. We believe that with longer opportunity for deep sleep, IDRX mode has more potential for higher power saving and battery life improvement and requires more research focus. Moreover, the proposed SPOP would serve better than using WUS for IDRX as it circumvents the need to design and implement additional WUS for IDRX mechanism while also facilitating early paging indication. Thus, SPOP saves not only more power at the UE but also precious radio resources.

Table 1: Related Work.

Technology Approach	Objective(s)	Work summary
Power saving at the network	Evaluate EE in 5G networks.	-Considering cloud-RAN [14] -BS selection optimization [15] -BS power-off/on by graph-theory [16] -Green cloudlet network [17]
Power saving at the terminal	Survey of the candidate techniques.	Discontinuous reception, secondary cell dormancy, cross-slot scheduling, etc. [20]
Wake-up signal (WUS) CDRX	Power saving in connected mode DRX.	Periodically monitoring of WUS [21] First offline modeling then online optimization of the wake-up scheduler parameters [22].
Wake-up signal (WUS) CDRX	Power saving and reduced wake-up delay.	A three-state semi-Markov CDRX model with adjustable DRX cycle adaptive switching [23].
Wake-up signal (WUS) CDRX	Effect on DRX for different traffic scenarios.	Pre-grant message (PGM), a narrow-band control plane signaling is introduced [7].
Wake-up signal (WUS) CDRX	Considering UEs capacity, the power consumption at BS is optimized .	Handover, signaling bits, availability and power consumption linked to the data traffic [24]
Paging Monitoring IDRX	UE power saving.	Two types of PO monitoring. Default IDRX cycle length and UE negotiated cycle length are manipulated [26].

3. Split PO Paging (SPOP)

According to current 3GPP specifications on NR, the SS Burst set comprising of multiple SSB's are transmitted periodically with the default setting as 20 ms [20]. The number of times SS burst set is monitored for SSB measurements is critical to the pre-wakeup duration in directional IDRX. It is notable that more than one SSB burst measurements are required in every IDRX cycle as shown in Figure 1(b) [11]. The multiplicity in SSB burst measurement is needed to decode PDSCH as it is more sensitive to the time-frequency synchronization error, especially when reference signal density is low [11]. Furthermore, the limited UE's receiver antenna capabilities also necessitate several SSB burst measurements for time-frequency synchronization to decode PDSCH [11]. PDCCH monitoring on the other hand can suffice with single SSB measurement for synchronisation and do not need multiple SSB measurements. By splitting PDCCH monitoring from PDSCH decoding, the pre-wake overheads, essentially required for PDSCH decoding, can be reduced. This procedure is very effective when there is low paging arrival in an IDRX cycle. In practice, UE's frequently experience POs without any paging message. Such POs do not require PDSCH decoding and SPOP allows UE's to skip inessential SSB measurements in such POs. The proposed SPOP, is shown in Figure 4. It can be compared to existing 5G-IDRX scenario depicted in Figure 1(b). The SSB burst transmission is periodic and thus, results in the time gap between SSB measurement instance(s) and PO during which the UE cannot transit to deep sleep. Thus, distributive SSB burst measurements are interleaved with light sleeps in between them and the PO as shown in Figure 1(b) and Figure 4. When PDCCH for paging is absent in PSO-1, the UE can transit to deep sleep as shown in Figure 4 case 2. Only when PDCCH indicates presence of paging in PSO-1 then multiple SSB measurements are performed as shown in Figure 4 case 1. To ensure that the required SSB burst measurements are easily performed when necessary (case 1), PSO-1 and PSO-2 should be aligned in multiples of SSB burst transmission duration plus the related light sleep. In this way when the PDCCH indicates paging arrival, the extra SSB measurements are easily performed without any extra overheads. Thus, in SPOP, PDCCH monitoring acts as an early indication that can inform UE whether to measure multiple SSB bursts and decode PDSCH or continue to sleep. Moreover, unlike WUS, there is no need to design, implementation and resource allocation for an extra signaling for early indication.

Though the deep sleep duration shows sharp contrast in case 1 and case 2 of Figure 4, the actual power saving depends upon the paging arrival rate. Thus, to ascertain the probabilities of case 2 and case 1 in Figure 4, we use Markov's state diagram as shown in Figure 5. A Markov chain is a Markov process that helps to predict the status of an object or phenomenon at future times. The Markov process is used as the probability of a transition from state m to state n. It does not depend on the global time and only depends on the time interval available for the transition [27]. Proposed Markov's state diagram for SPOP is shown in Figure 5, has the following states, time intervals and transitions:

1. In state $S_{1,i}$, we consider a combination of the first SSB measurement and PDCCH monitoring in PSO-1 along with the intermediate light

sleep. State $S_{1,i}$ also comprises of Deep Sleep-1, which is always supported indifferent of presence or absence of paging in PSO-1. Thus, the duration of $S_{1,i}$ is equal to $T_{DS1} + T_{SSB} + T_{LS} + T_{PDCCH}$, where, T_{DS1}, T_{SSB}, T_{LS} and T_{PSO-1}, respectively are the deep sleep duration-1, SSB measurement duration, light sleep duration and PSO-1 duration. In every IDRX cycle, UE has to measure SSB at least once to receive PDCCH for paging indication. If paging is not received, UE transits to $S_{3,i}$ with probability $P_{1i,3i}$, where it can enjoy the extra deep sleep avoiding inessential SSB measurements. However, if the PDCCH for paging is received, the UE transits to the state $S_{2,i}$ with probability $P_{1i,2i}$. Note that i represents the number of IDRX cycles in the Markov chain, and it varies as $1, 2, 3, 4, ..., n, (n + 1)...$ for IDRX cycle number $1, 2, 3, 4, ..., n, (n + 1)...$ respectively. Also note that, i does not increment in these transitions to $S_{2,i}$ and $S_{3,i}$ from $S_{1,i}$ as UE remains in the same IDRX cycle.

2. $S_{2,i}$ represents the combination of additional m SSB measurements for PDSCH decoding and duration of PSO-2 along with intermediate light sleeps. The duration of $S_{2,i}$ is therefore equal to $m * T_{SSB} + (m + 1) * T_{LS} + T_{PSO\text{-}2}$. If the UE ID is included in the PDSCH message, UE

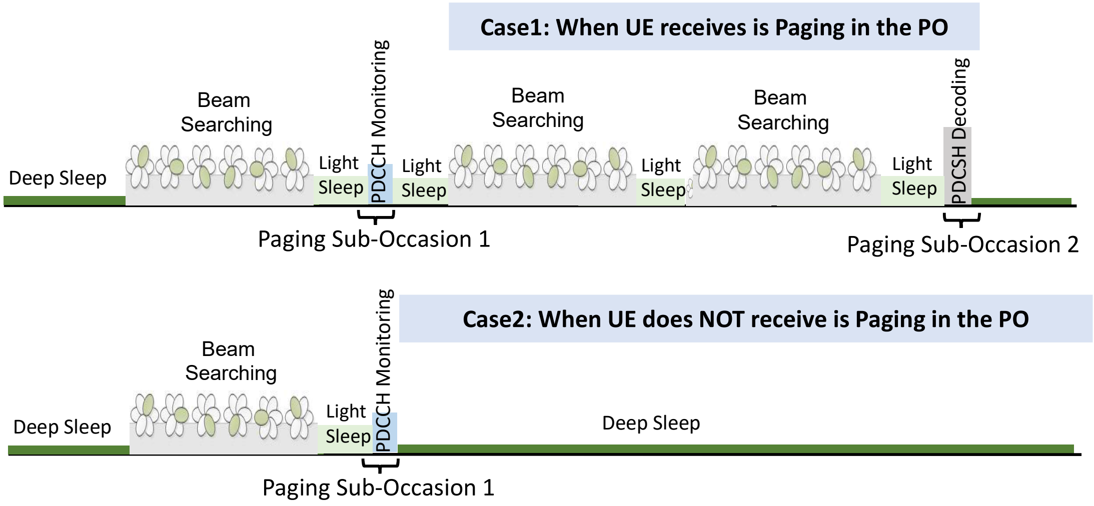


Figure 4: Split PO for UE's Power Saving in B5Gs

transits to active state $S_{0,0}$ with probability $P_{2i,00}$, else, it transits to $S_{1,i+1}$ with probability $P_{2i,1(i+1)}$. Here, the increment in i indicates the transition to the next IDRX cycle.

3. $S_{3,i}$ represents the extra Deep Sleep-2 of duration T_{DS2}. This deep sleep occurs only when the PDCCH for paging is not received in PSO-1, as shown in Figure 4 case 2 and is equal to $m{*}T_{SSB}+(m+1){*}T_{LS}+T_{PSO\text{-}2}$. The UE transits from $S_{3,i}$ to $S_{1,i+1}$ with probability $P_{3i,1(i+1)}$ such that i increments and UE moves to next IDRX cycle with probability one.

4. $S_{0,0}$ represents the active state where the UE is not in the IDRX cycle. If UE keeps receiving data packets and does not get the opportunity to transit to IDRX mode, it remains in the active state with the probability $P_{00,00}$, else it transits to $S_{1,1}$ with probability $P_{00,11}$.

We can obtain the transition probabilities for state model in Figure 2 as:

$$
\begin{align}
P_{00,00} &= (1 - e^{-\lambda T_I}) \tag{1}\\
P_{00,11} &= (e^{-\lambda T_I}) \tag{2}\\
P_{1i,2i} &= 1 - e^{-\lambda (T_{DS1}+T_{SSB}+T_{LS}+T_{PSO\text{-}1})M} \tag{3}\\
P_{1i,3i} &= e^{-\lambda (T_{DS1}+T_{SSB}+T_{LS}+T_{PSO\text{-}1})M} \tag{4}\\
P_{2i,00} &= 1 - e^{-\lambda (m*T_{SSB}+(m+1)*T_{LS}+T_{PSO\text{-}2})} \tag{5}\\
P_{2i,1(i+1)} &= e^{-\lambda (m*T_{SSB}+(m+1)*T_{LS}+T_{PSO\text{-}2})} \tag{6}\\
P_{3i,1(i+1)} &= 1 \tag{7}
\end{align}
$$

where, λ is paging arrival rate, T_I is the inactivity duration and $i = 1, 2, 3...n$ (For analysis purpose, we considered “n” IDRX cycles). It is notable that several UE’s can be configured in each PO [28]. Thus, M is a crucial parameter in $P_{1i,2i}$ and $P_{1i,3i}$ since the PDCCH for paging would be present even if at least one of M UEs is paged. The consolidated probability matrix corresponding to the state diagram in Figure 2 can be obtained as:

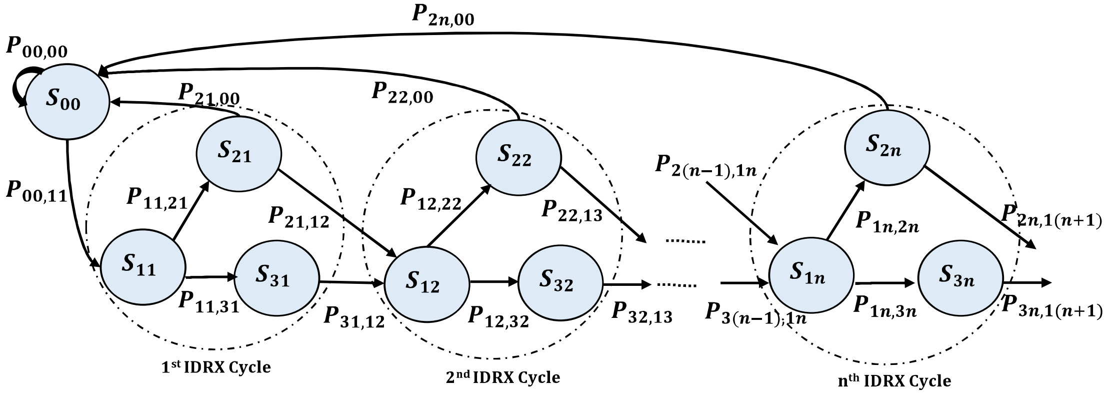


Figure 5: Markov Chain Modelling for proposed Split PO Paging (SPOP)

$$P = \begin{bmatrix} P_{00,00} & P_{00,11} & 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ 0 & 0 & P_{11,21} & P_{11,31} & 0 & \dots & 0 & 0 & 0 \\ P_{21,00} & 0 & 0 & 0 & P_{21,12} & \dots & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & \dots & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ P_{22,00} & 0 & 0 & 0 & 0 & \dots & 0 & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \dots & \vdots & \vdots & \vdots & \\ 0 & 0 & 0 & 0 & 0 & \dots & 1 & P_{1n,2n} & P_{1n,3n} \\ P_{2n,00} & 0 & 0 & 0 & 0 & \dots & P_{2n,1n} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \dots & 1 & 0 & 0 \end{bmatrix}$$

Let Π_{1i} for $i = 1, 2, 3...n$ denote the steady state probability of staying in state $S_{1,i}$ of the Markov chain. Using $\sum_i \Pi_{k,i} = 1$ and balance equation $\Pi = \sum_k \pi_{ki} P_{ki,ji}$, we can calculate the steady state probability of staying in the state $S_{1,i}$. The steady state probabilities Π_{00} and Π_{11} for states $S_{0,0}$ and $S_{1,1}$, respectively are given as:

$$\Pi_{00} = \frac{\left(\sum_{i=1}^{n} \Pi_{2i} P_{2i,00} \right)}{(1 - P_{00,00})}, \tag{8}$$

$$\Pi_{11} = (\Pi_{00})(P_{00,11}) \tag{9}$$

The steady state probabilities of staying in the state $S_{1,i}$, $S_{2,i}$ and $S_{3,i}$, can be obtained as

$$\Pi_{1i} = \begin{cases} \Pi_{2(i-1)}P_{2(i-1),1i} + \Pi_{3(i-1)}, & i = 2, 3, ..(n-1) \\ \Pi_{2(n-1)}P_{2(n-1),1n} + \Pi_{3(n-1)} + \Pi_{2(n-1)}P_{2n,1n} + \Pi_{3n}, i = n \end{cases} \tag{10}$$

$$\Pi_{2i} = \Pi_{1i}P_{1i,2i}, \qquad i = 1, 2, ...n \tag{11}$$

$$\Pi_{3i} = \Pi_{1i}P_{1i,3i}, \qquad i = 1, 2, ...n \tag{12}$$

To evaluate power consumed in different states, it is important to evaluate holding times for those states [29]. Holding time is the time UE spends in the given state. We can find the holding time of states $S_{0,0}$, $S_{1,i}$, $S_{2,i}$, and $S_{3,i}$ as:

$$E[H_{00}] = \frac{1 - e^{-\lambda T_I}}{(1 - e^{-\lambda})e^{-\lambda T_I}} \tag{13}$$

$$E[H_{1i}] = \frac{1 - e^{-\lambda M(T_{DS1} + T_{SSB} + T_{LS} + T_{PDCCH})}}{\lambda M} \tag{14}$$

$$E[H_{2i}] = \frac{1 - e^{-\lambda(TDS2)}}{\lambda}, \tag{15}$$

$$E[H_{3i}] = T_{DS2} \tag{16}$$

where, $T_{DS2} = m * T_{SSB} + (m+1) * T_{LS} + T_{PDSCH}$. Using the holding times and steady state probabilities along with the power consumed in that state, we can evaluate average power consumption Γ_s in SPOP as:

$$\Gamma_s = \frac{\sum_{i=1}^{n}(\Pi_{1i}E_{H_{1i}}PW_{1i} + \Pi_{2i}E_{H_{2i}}PW_{2i} + \Pi_{3i}E_{H_{3i}}PW_{3i})}{\sum_{i=1}^{n}(\Pi_{1i}E_{H_{1i}} + \Pi_{2i}E_{H_{2i}} + \Pi_{3i}E_{H_{3i}})} \tag{17}$$

where, PW_{1i}, PW_{2i} & PW_{3i} are the power consumption values in the states $S_{1,i}$, $S_{2,i}$ & $S_{3,i}$, respectively. They can be obtained by summing the power consumed in different operations performed in the given state. Thus, $PW_{1i} = PW_{DS} + PW_{SSB} + PW_{LS} + PW_{PSO\text{-}1}$, $PW_{2i} = m * PW_{SSB} + (m+1) * PW_{LS} + PW_{PSO\text{-}2}$ and $PW_{3i} = PW_{DS}$. Here, PW_{DS}, PW_{SSB}, PW_{LS}, $PW_{PSO\text{-}1}$ and $PW_{PSO\text{-}2}$, respectively are the power consumed in deep sleep, SSB measurement, light sleep, PDCCH monitoring and PDSCH decoding. The power consumption would affect the UE's battery life, which we subsequently evaluate using Peukert's law. Peukert's law [30] is one of the simple model to predict battery lifetimes while taking into account the non-linear properties of the battery. Peukert's law relates the battery lifetime (ϑ) to the discharge rate as $\vartheta = \frac{a}{I^b}$, where, I is discharge current, a and b are constant. Ideally a should be equal to battery capacity and b lies between 1.2 and 1.7 for most batteries [30]. This model is applicable for the constant continuous load. For non-constant load, Rakhmatov and Vrudhula proposed the extended version of Peukert's law [30] that we can be use for the evaluation of battery life as:

$$\vartheta = \frac{a}{[\sum_{m=1}^{p} I_m(t_m - t_{m-1})/\vartheta]^b} \tag{18}$$

For $p = 1$, the equation (18) reduces to $\frac{a}{I^b}$ [30].

To understand the cost of improved power saving and better battery life, we also evaluate delay. Delay occurs as the UE wakes up only periodically to monitor PO while the actual message might arrive in between the POs when the UE is asleep. The decrease in power consumption can adversely affect the delay in SPOP which makes the analysis of this tradeoff essential. Using the work [31][32] the average delay is calculated as:

$$\delta_{SPOP} = \frac{\sum_{i=1}^{n} \delta_{S_{1,i}} P_{S_{1,i}} + \delta_{S_{2,i}} P_{S_{2,i}} + \delta_{S_{3,i}} P_{S_{3,i}}}{n} \tag{19}$$

where $P_{S_{1,i}}$, $P_{S_{2,i}}$ & $P_{S_{3,i}}$ is the probability of paging request and $\delta_{S_{1,i}}$, $\delta_{S_{2,i}}$ & $\delta_{S_{3,i}}$ is the buffering delay during $S_{1,i}$, $S_{2,i}$ and $S_{3,i}$, respectively. Let, $T_{S1i} = T_{DS1} + T_{SSB} + T_{LS} + T_{PDCCH}$, $T_{S2i} = m * T_{SSB} + (m+1) * T_{LS} + T_{PSO\text{-}2}$ and $T_{S3i} = T_{DS2}$; using work [31], [32] the $\delta_{S_{1,i}}$, $\delta_{S_{2,i}}$ & $\delta_{S_{3,i}}$ are computed as:

$$\delta_{S_{1,i}} = T_{S1i} - \frac{1 - e^{-\lambda_k T_{S1i}}}{\lambda_k} \tag{20}$$

$$\delta_{S_{2,i}} = T_{S2i} - \frac{1 - e^{-\lambda_k T_{S2i}}}{\lambda_k} \tag{21}$$

$$\delta_{S_{3,i}} = T_{S3i} - \frac{1 - e^{-\lambda_k T_{S3i}}}{\lambda_k} \tag{22}$$

The probability of paging request $P_{S_{1,i}}$, $P_{S_{2,i}}$ & $P_{S_{3,i}}$ is given as [31], [32]

$$P_{S_{1,i}} = \alpha \left(\frac{e^{-} \lambda_k T_{S1i}}{1 - e^{-\lambda_k T_{Si}}} \right) \tag{23}$$

$$P_{S_{2,i}} = \beta \left(\frac{e^{-} \lambda_k T_{S2i}}{1 - e^{-\lambda_k T_{S2i}}} \right) \tag{24}$$

$$P_{S_{3,i}} = \gamma \left(\frac{e^{-}\lambda_k T_{S3i}}{1 - e^{-\lambda_k T_{S3i}}} \right) \tag{25}$$

where $\alpha = \left(1 - e^{-\lambda_k T_{Si}}\right) \left(e^{-\lambda_k (T_i - T_{S1i})}\right)$,
$\beta = \left(1 - e^{-\lambda_k T_{S2i}}\right) \left(e^{-\lambda_k (T_i + T_{S1i} - T_{S2i})}\right)$ and
$\gamma = \left(1 - e^{-\lambda_k T_{S3i}}\right) \left(e^{-\lambda_k (T_i + T_{Si} - T_{S3i})}\right)$.

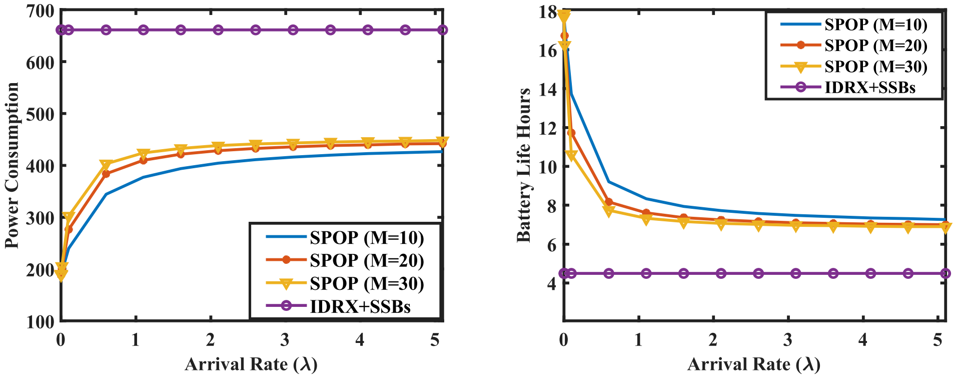
Finally, we would like to point out that while manifesting power saving at the UE, the location or mobility of UE is inconsequential. The PDCCH/PDSCH for paging are the broadcast signal because the location of the UE within the cell is not known. These signals are intended for all the UE's whether they are near the base station or at the cell edge. Thus, the location of the UE within the cell would have no effect on the split PO paging. Furthermore, in proposed SPOP, we considers appropriate time interval between PSO-1 where the PDCCH is monitored and PSO-2 where the PDSCH is decoded. Thus, if PDCCH indicates the presence of paging there is enough time for UE to measure SSBs for PDSCH decoding even if it is moving within the cell. From mobility point of view this scenario is similar to the existing system as in that case aswell UE first measures SSBs then monitors PDCCH/decode PDSCH. Moreover, the time duration is very small (20ms) between last SSB burst measurement and PDCCH monitoring in existing system or PDSCH decoding in SPOP. Thus, the change in UE location would be very small.

4. Performance Analysis of SPOP

The power consumption in directional IDRX is high due to long pre-wake up with multiple SSB measurements for time/frequency synchronization to prepare UE for PDSCH decoding. Depending upon the SINR (Signal-to-interference-plus-noise ratio) before the paging reception in the PO, the UE can configure up to three SSB burst measurements [2, 11]. Thus, in

Table 2: Performance Parameters

Parameter	**Value**
DRX Cycle	1280 ms
No. of beams	$16 \sim 128$
[a, b]	[5000 mAh, 1.1]
$[T_{PDCCH}, T_{PDSCH}, T_{WUS}, T_{LS}]$	[0.2, 0.2, 0.2, 20] ms
$[PW_{PDCCH}, PW_{PDSCH}, PW_{WUS}]$	[100, 100, 100]
$[PW_{SSB}, PW_{LS}, PW_{DS}]$	[100, 20, 1]
λ	$1e{-}7 \sim 5$



(a) (b)

Figure 6: (a) Power Consumption with Varying Arrival Rate (b) Battery Life with Varying Arrival Rate

accordance with the current 3GPP study, we consider one SSB measurements for PDCCH monitoring and $m = 2$ additional SSB measurements for PDSCH decoding for our analysis. We obtain the other parameters given in Table 2 from 3GPP contributions [2, 11]. The IDRX cycle length in considers as $D = 1280$ ms and the sleep time T_{DS1} is evaluated as $(D - (3T_{SSB} + 4T_{LS} + PSO\text{-}1 + PSO\text{-}2))$ based on Figure 4 case 1. Same parameters applied to aforesaid analysis also used to obtain Figure 3, presented earlier in the paper. It is to be noted that the power-saving in SPOP is achieved only when the paging indication in PSO-1 is absent. Thus, in Figure 6(a), we show the power consumption of SPOP with respect to varying paging arrival rates λ. The figure also gives average power consumption for the existing system. As expected, the average power consumption in SPOP is substantially lower (around 51%) than the existing system in which UE is always performing elaborate pre-wake. SPOP circumvents the additional processing when not necessary in the absences of PDCCH for paging. Furthermore, SPOP performs better even when the high arrival rate is considered. The figure also depicts the effect of configured number of UEs in a PO. As expected when M is high, the power consumption is high as the probability of receiving paging increases. In existing system whether or not paging is present, the UE should monitor all the SSBs as well as decode PDSCH. Thus, for the existing IDRX (Figure 1(b)), the power consumption is almost same for all arrival rates. When paging is absent, UE would not decode PDSCH and some power would be saved in existing system as well. However, that value is very less compared to summation of power requirement for multiple SSB measurements, intermediate light sleeps and PDSCH decoding. In existing directional IDRX, pre-wakeup is elaborate in every IDRX cycle even when paging is absent, as a result, the battery life in SPOP is higher compared to the existing system. It is almost twice and even more than that of the existing IDRX even for a high arrival rate of $\lambda = 5$ as shown in Figure 6(b). For, $M = 10$, the battery life improvement can be as high as 61% than the existing IDRX with multiple SSB burst measurements.

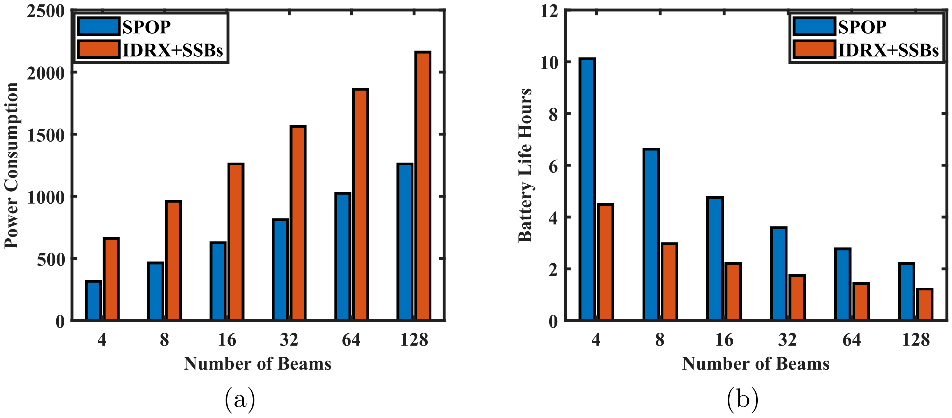


Figure 7: (a) Power Consumption with Varying Number of Beams (b) Battery Life with Varying Number of Beams

In Figure 7(a), we show the effect of increase in number of beams on power consumption. As the carrier frequency increases, the number of beams would also increase. More beams would increase the time duration of every SSB burst set. As expected, with more beams, the power consumption would increase. However, compared to the existing IDRX the percentage of power saved in SPOP improves as number of beams increase. The power saving can be as high as 46.7% compared to existing system. When the number of beams and subsequently duration per SSB burst is high, SPOP saves more power by avoiding the non-essential SSB measurements. The increase in number of beams would have detrimental effect on the UE's battery life as shown in Figure 7(b). It is clear from Figure 7 that SPOP would remain relevant for higher number of beams expected in future B5G wireless networks utilizing carriers in the terahertz range. The proposed SPOP can manifest 53% saving on battery life even with high number of beams by enabling extra deep sleep when paging is absent.

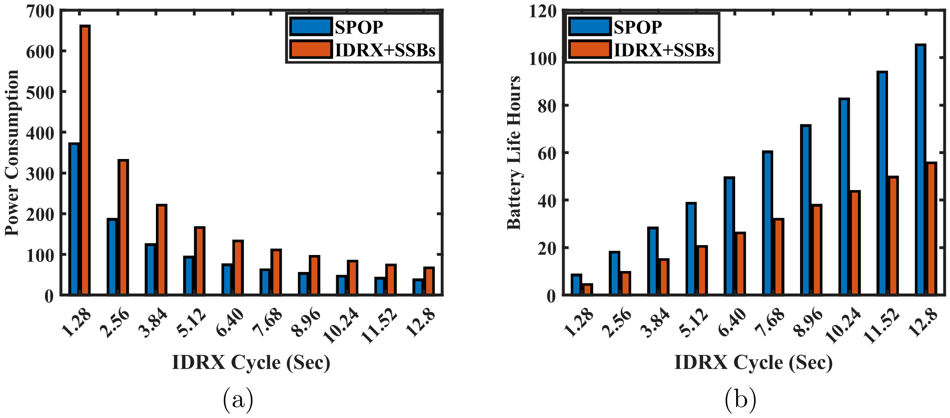
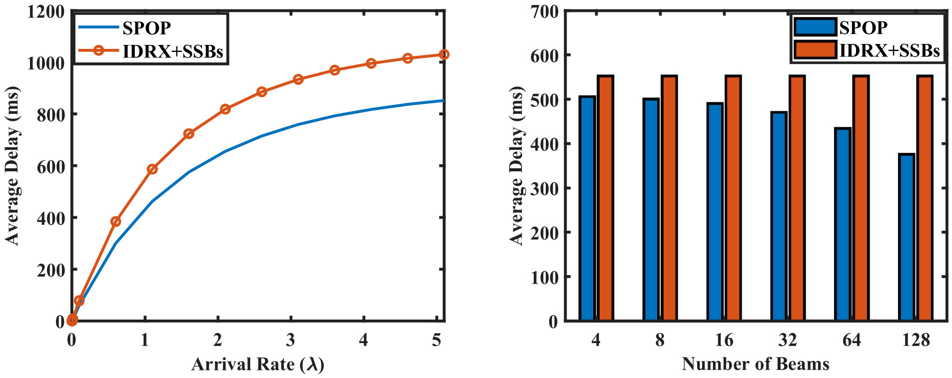


Figure 8: (a) Power Consumption with Varying IDRX Cycle Length (b) Battery Life with Varying IDRX Cycle Length

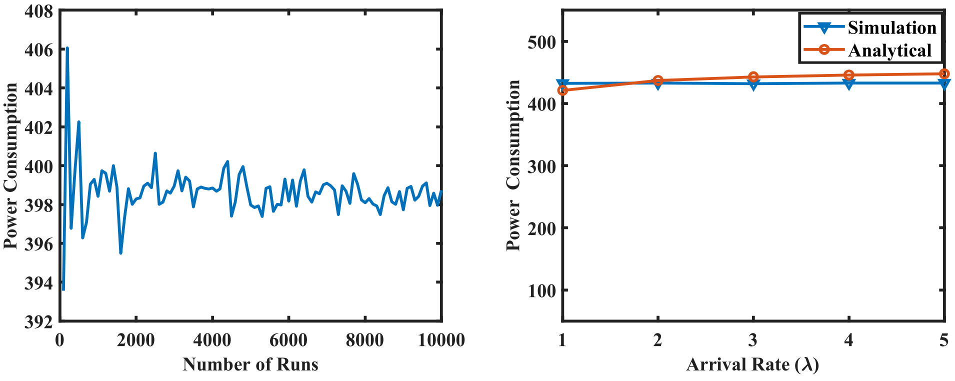
The effect of IDRX cycle length on power saving and battery life is shown in Figure 8 for the arrival rate of $\lambda = 1$. In B5G networks, the UE's are expected to support several new applications and services that may manifest less frequent traffic eg. non critical applications to enable some part of Internet of Things. Thus, it is important to consider the advantages of SPOP when the cycle length is more than the considered configuration of 1280 ms. In Figure 8, while the value of D increases in multiples of 1280 ms, the other parameters remain the same. With the increase in the cycle length, the UE's deep sleep time increases. As expected, with the higher IDRX cycle length, the power consumption reduces sharply. When the IDRX cycle length is long the number of times SSB measurements are done reduces substantially. In such a case power consumption for the existing case as well as SPOP decrease. However, the SPOP performs better than the existing system even when the SSB measurements are performed for lower percentage of time in the IDRX cycle length. With varying IDRX cycle length SPOP can manifest upto 43% power saving and 47% battery life improvement for arrival rate of $\lambda = 1$ compared to the existing IDRX system imbued with multiple SSB burst measurements in every cycle.



(a) (b)

Figure 9: (a) Average Delay with Random Arrival Rate (b) Average Delay with Varying Number of Beams

It is natural to observe the effect of delay on IDRX cycle that is essentially introduced for power saving and battery life improvement. This is because the connection requests arriving during deep sleep, light sleep and SSB measurement duration are buffered till the UE wakes up in a PO for PDCCH monitoring. In Figure 9(a), we show the effect on delay with the varying arrival rate while comparing it to the existing system. As observed form Figure 9(a) the delay increases with increase in arrival rate for both SPOP and existing system since more request are buffered with higher arrival rate. However, the delay observed by SPOP is less than existing IDRX that has inevitable SSBs measurement. This is because a paging request can be received during the $S_{1,i}$ state which is before the elaborate SSB measurements and light sleep duration. On the other hand, in the existing system (IDRX with SSBs) the UE receives the paging request after deep sleep, elaborate SSB measurements and light sleep time. In SPOP if paging is received in $S_{1,i}$ then only the UE transits to $S_{2,i}$ for addressing the request. On the other occasions when PDCCH for paging is absent, then there is no effect on delay at all. We also show variations in delay with varying number of beams as depicted in Figure 9(b). In case of SPOP, the delay observed by UE decreases with increase in number of beam, as more number of beams reduces the UE's deep sleep duration. In practice, different UEs configured in a cell may have different arrival rates. Moreover, considering the dynamics, some UEs may exit the tracking area while the new ones might be added. To further highlight the effect of variable arrival rate and the number of UE's configured in a PO, we consider Figure 10(a) which shows more realistic results. In Figure 10(a), for every IDRX cycle, we generate a random arrival in range ($\lambda \in 0,\ 3$) and random number for UE's configured in a PO. The simulations are run for $10,000$ IDRX cycles and a running average over every 1000 cycles is evaluated. The figure shows the advantages of SPOP over a long interval. It can be observed that the variations in power consumption very over a small range from 394 to 408. Thus, SPOP performance in not compromised in the dynamic environment that is usually expected in a wireless network.



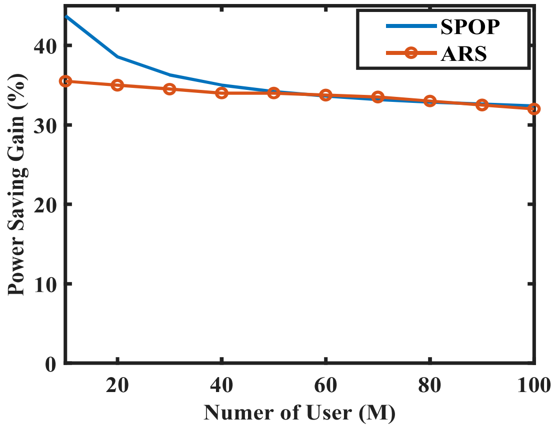
(a) (b)

Figure 10: (a) Power Consumption with Random Arrival Rate and Users (b) Analytical & Simulation Results

In Figure 10(b), we validate our analysis through simulation studies. For simulations, we consider the following steps

1. We consider a cell where we uniformly distribute UE's with Poisson arrival. For our simulations, we have considered 30 UEs configured in a PSO-1 with the arrival rate between $[1, 5]$.

2. We generate paging request time for all the configured UE's according to Poisson's distribution with the given arrival rate λ. For every UE the paging occurrence time is recorded as $t_i = \sum_1^i x_i$, where x_i is a random variable.



,

Figure 11: SSB Transmission and Beam Alignment.

3. The time line obtained in previous step is then overlapped with the UE's IDRX time line with cycle length of 1280 ms to find the IDRX cycles when paging is received. Such arrival for all the $M = 30$ configured UEs is then plotted and overlapped. This is done as all the M UEs should monitor paging even if one receives arrival.

4. We consider duration of an hour and track for one specific UE the number of IDRX cycles when paging was absent and occasions when it was present. Subsequently, we calculate the power consumption considering respectively one or three SSB measurements based on presence and absence of paging during each trial.

5. The procedure is repeated for 50 trials. Finally, we calculate the average power and compare it with the analytical result.

As expected from Figure 10(b), the power consumption increases with an increase in the arrival rate. The simulation results follow the same trends as analytical results and are comparable to the analytical results.

Finally, in figure 11 the number of UEs in a PO are varied and power saving gains are analysed for proposed SPOP and ARS (Additional Reference Signal) scheme in [33]. We compare with ARS as it is similar to early paging indication manifested in PSO-1 of our proposal. It is observed from figure 11 that power saving gain decreases with increases in the number of UEs.

This is expected since the large number of configured UEs in a PO would increase the chance of paging requests in an IDRX cycle. It is notable that all the UEs configured in a PO would perform SSB measurements, monitor PDCCH and decode PDSCH even if one UE receives paging message. When compared with the ARS scheme of [33], the performance of SPOP for a lower number of UEs is better as unnecessary SSB measurements are avoided more frequently, which reduces UE's pre-wakeup energy overheads. For a high number of UEs configured in a PO, the performance of SPOP is almost similar to ARS scheme as the chance of several SSB measurements increases with more possibility of paging arrival.

5. Conclusion

In this paper, we propose and analyze our novel proposal split PO paging (SPOP) by using Markov chain modeling. SPOP can reduce UE's power consumption in directional Idle mode Discontinuous Reception (IDRX) of B5G networks by manifesting early paging indication. In B5G networks, the directional IDRX would require longer pre-wakeup in every cycle for beam tracking and time-frequency synchronization. Proposed SPOP is an IDRX optimization that provides early paging indication in order to avoid unnecessary processing and decoding when paging arrival is absent. In SPOP, when UE does not receive a page, it can enjoy extended deep sleep. SPOP manifests early paging by splitting the paging occasion into two sub-occasions while ensuring appropriate time gap between the two sub-occasion so that elaborate processing can be performed when paging is indicated. With varying paging arrival rate SPOP can save upto 50% power and 61% battery.

References

[1] M. Giordani, M. Polese, M. Mezzavilla, S. Rangan, M. Zorzi, Toward 6g networks: Use cases and technologies, IEEE Communications Magazine 58 (3) (2020) 55–61.

[2] G. 38.840, Study on User Equipment (UE) power saving in NR (Release 16), TR 38.840, 3rd Generation Partnership Project (3GPP) (June 2019).

[3] C.-W. Chang, J.-C. Chen, Um paging: Unified m2m paging with optimal drx cycle, IEEE Transactions on Mobile Computing 16 (3) (2016) 886–900.

[4] K. B. Letaief, W. Chen, Y. Shi, J. Zhang, Y.-J. A. Zhang, The roadmap to 6g: Ai empowered wireless networks, IEEE Communications Magazine 57 (8) (2019) 84–90.

[5] S. Goyal, H. Elkotby, R. Pragada, T. Haque, Reducing the paging overhead in highly directional systems, in: 2021 IEEE 93rd Vehicular Technology Conference (VTC2021-Spring), IEEE, 2021, pp. 1–7.

[6] J. Liu, K. Au, A. Maaref, J. Luo, H. Baligh, H. Tong, A. Chassaigne, J. Lorca, Initial access, mobility, and user-centric multi-beam operation in 5g new radio, IEEE Communications Magazine 56 (3) (2018) 35–41.

[7] S. Rostami, K. Heiska, O. Puchko, K. Leppanen, M. Valkama, Pre-grant signaling for energy-efficient 5g and beyond mobile devices: Method and analysis, IEEE Transactions on Green Communications and Networking 3 (2) (2019) 418–432.

[8] Qualcomm, Designing mobile devices for low power and thermal efficiency, white paper Qualcomm Technologies Technologies, Inc. (2013).

[9] G. 38.802, Study on New Radio Access Technology-Physical Layer Aspects, TS 38.802, 3rd Generation Partnership Project (3GPP), v14.0.0 (June 2017).

[10] X. Lin, J. Li, R. Baldemair, J.-F. T. Cheng, S. Parkvall, D. C. Larsson, H. Koorapaty, M. Frenne, S. Falahati, A. Grovlen, et al., 5g new radio: Unveiling the essentials of the next generation wireless access technology, IEEE Communications Standards Magazine 3 (3) (2019) 30–37.

[11] G. R1-2005388, Discussion on Paging Enhancements for Idle/Inactive Mode UE Power Saving, Tech. Rep. 36.331, Vivo, contribution, TSG RAN WG1 #102-e (2020).

[12] P. Gandotra, R. K. Jha, A survey on green communication and security challenges in 5g wireless communication networks, Journal of Network and Computer Applications 96 (2017) 39–61.

[13] S. Rostami, P. Kela, K. Leppanen, M. Valkama, Wake-up radio-based 5g mobile access: Methods, benefits, and challenges, IEEE Communications Magazine 58 (7) (2020) 14–20.

[14] M. Masoudi, M. G. Khafagy, A. Conte, A. El-Amine, B. Françoise, C. Nadjahi, F. E. Salem, W. Labidi, A. Süral, A. Gati, et al., Green mobile networks for 5g and beyond, IEEE Access 7 (2019) 107270–107299.

[15] W. Yu, H. Xu, A. Hematian, D. Griffith, N. Golmie, Towards energy efficiency in ultra dense networks, in: 2016 IEEE 35th International Performance Computing and Communications Conference (IPCCC), IEEE, 2016, pp. 1–8.

[16] M. J. Daas, M. Jubran, M. Hussein, Energy management framework for 5g ultra-dense networks using graph theory, IEEE Access 7 (2019) 175313–175323.

[17] X. Sun, N. Ansari, Green cloudlet network: A sustainable platform for mobile cloud computing, IEEE Transactions on Cloud Computing 8 (1) (2017) 180–192.

[18] G. 38.300, Radio Access Network NR; NR and NG-RAN overall description, TR 38.300, 3rd Generation Partnership Project (3GPP) (Jan 2019).

[19] 3rd Generation Partnership Project, 3gpp release 16 timeline, available [online]:, `https://www.3gpp.org/release-16` (July 3, 2020).

[20] Y.-N. R. Li, M. Chen, J. Xu, L. Tian, K. Huang, Power saving techniques for 5g and beyond, IEEE Access 8 (2020) 108675–108690.

[21] S. Rostami, S. Lagen, M. Costa, P. Dini, M. Valkama, Optimized wake-up scheme with bounded delay for energy-efficient mtc, in: 2019 IEEE Global Communications Conference (GLOBECOM), IEEE, 2019, pp. 1–6.

[22] S. Rostami, H. D. Trinh, S. Lagen, M. Costa, M. Valkama, P. Dini, Proactive wake-up scheduler based on recurrent neural networks, in: ICC 2020-2020 IEEE International Conference on Communications (ICC), IEEE, 2020, pp. 1–6.

[23] F. Yi, Y. Ji, Z. Lao, J. Wang, An enhanced discontinuous reception mechanism for power saving in 5g, in: 2020 IEEE 92nd Vehicular Technology Conference (VTC2020-Fall), IEEE, 2020, pp. 1–5.

[24] A. RamÃrez-Arroyo, P. H. Zapata-Cano, n. Palomares-Caballero, J. Carmona-Murillo, F. Luna-Valero, J. F. Valenzuela-ValdÃ©s, Multilayer network optimization for 5g amp; 6g, IEEE Access 8 (2020) 204295–204308. doi:10.1109/ACCESS.2020.3036744.

[25] 3rd Generation Partnership Project, 3gpp release 17 timeline, available [online]:, `https://www.3gpp.org/news-events/2145-rel-17_newtimeline` (December 14, 2020).

[26] A. Agiwal, M. Agiwal, Enhanced paging monitoring for 5g and beyond 5g networks, IEEE Access 10 (2022) 27197–27210.

[27] M. Pinsky, S. Karlin, An introduction to stochastic modeling, Academic press, 2010.

[28] M. Agiwal, H. Jin, Directional paging for 5g communications based on partitioned user id, Sensors 18 (6) (2018) 1845.

[29] E. Chavarria-Reyes, E. Fadel, S. Almasri, M. A. Malik, Reducing the energy consumption at the user equipment through multi-stream cross-carrier-aware discontinuous reception (drx) in lte-advanced systems, Journal of Network and Computer Applications 64 (2016) 43–61.

[30] M. Jongerden, B. Haverkort, Battery modeling, Enschede, January (2008) 38.

[31] A. T. Koc, S. C. Jha, R. Vannithamby, M. Torlak, Device power saving and latency optimization in lte-a networks through drx configuration, IEEE Transactions on wireless communications 13 (5) (2014) 2614–2625.

[32] Y. Liu, M. Huynh, A. Mangla, D. Ghosal, Performance analysis of adjustable discontinuous reception (drx) mechanism in lte network, in: 2014 23rd Wireless and Optical Communication Conference (WOCC), IEEE, 2014, pp. 1–6.

[33] T. Kim, Y. Kim, Q. Lin, F. Sun, J. Fu, Y. Kim, A. Papasakellariou, H. Ji, J. Lee, Evolution of power saving technologies for 5g new radio, IEEE Access 8 (2020) 198912–198924.