

Enhanced Paging Monitoring for 5G and Beyond 5G Networks

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ABSTRACT User experience, characterized by not only data rate and latency but also power consumption, is one of the major drivers for the success of 5G and Beyond-5G (B5G) networks. User Equipment (UE) power saving enhancements are at the forefront of ongoing discussions in 3GPP for next generation radio standards. Idle mode Discontinuous Reception (IDRX) is an important mechanism for UE's power saving. However, IDRX in 5G/B5G networks is more challenging than in legacy networks. UE is required to measure Synchronization Signal Block(s) (SSBs) for Physical Downlink Shared Channel (PDSCH) and Physical Downlink Common Control Channel (PDCCH) reception in every paging occasion (PO) of IDRX cycle in 5G/B5G networks. Furthermore, PDSCH decoding is very sensitive to the time-frequency synchronization error and requires multiple SSB measurements before every PO. In this paper we present an Enhanced Paging Monitoring (EPM) for reducing the impediments on IDRX in 5G/B5G due to SSB measurements and related overheads. We also extend our EPM proposal by incorporating paging early indication. The proposed EPM can manifest up to 37% more power saving compared to existing system while considering multiple SSB measurements that are essential to 5G/B5G networks.

INDEX TERMS IDRX, new radio (NR), paging, SSBs, 5G.

I. INTRODUCTION

3GPP standard organization has completed the first release of 5G standards called Release 15 New Radio (NR) in 2018. This release primarily addresses the requirements of enhanced Mobile Broadband (eMBB) services such as tens of Gbps data rate, low latency (10 ms for control plane and 4 ms for user plane) and high mobility (up to 500 km/hr) [1]. The first release of 5G standards also includes some basic power saving mechanisms such as Discontinuous Reception (DRX) in downlink, bandwidth adaptation, flexible reference signal and control channel design [2]. Additional techniques to minimize UE's power consumption in connected mode, such as power saving signal for discontinuous reception, secondary cell dormancy, cross-slot scheduling, etc. has been incorporated in the second release (3GPP Release 16) of the 5G standards completed in 2020 [2]. User experience is key to 5G/B5G success, not only in terms of data rate and latency but also UE's power consumption. Thus, 3GPP is currently

studying enhancements to UE's power saving in idle mode as part of its release 17, scheduled for completion in 2022 [3].

Idle mode-Discontinuous Reception (IDRX) is an effective mechanism that facilitates deep sleep for UE's power conservation [4]. In IDRX, UE wakes up at regular intervals (i.e. every IDRX cycle) for short periods to receive paging message, System Information (SI) update notifications and emergency (Earthquake/Tsunami Warnings (ETWS), Commercial Mobile Alerts (CMAS)) notifications, in its Paging Occasion (PO) [5], [6]. Each cell broadcasts a default IDRX cycle length which is common for all the UEs camped in that cell. Based on its power consumption requirements, UE also negotiates a UE specific IDRX cycle length with the core network which can be different from the default IDRX cycle length. However, UE monitors PO in every IDRX cycle where the length of IDRX cycle is minimum of the default IDRX cycle and UE specific IDRX cycle [7]. The aforesaid minimum setting implies that the UE should wake up every default IDRX cycle even when it needs to conserve more power and is configured with longer than the default IDRX cycle as shown in Figure 1. Figure 1(a) shows the POs of UE corresponding to default IDRX cycle. Figure 1(b) shows

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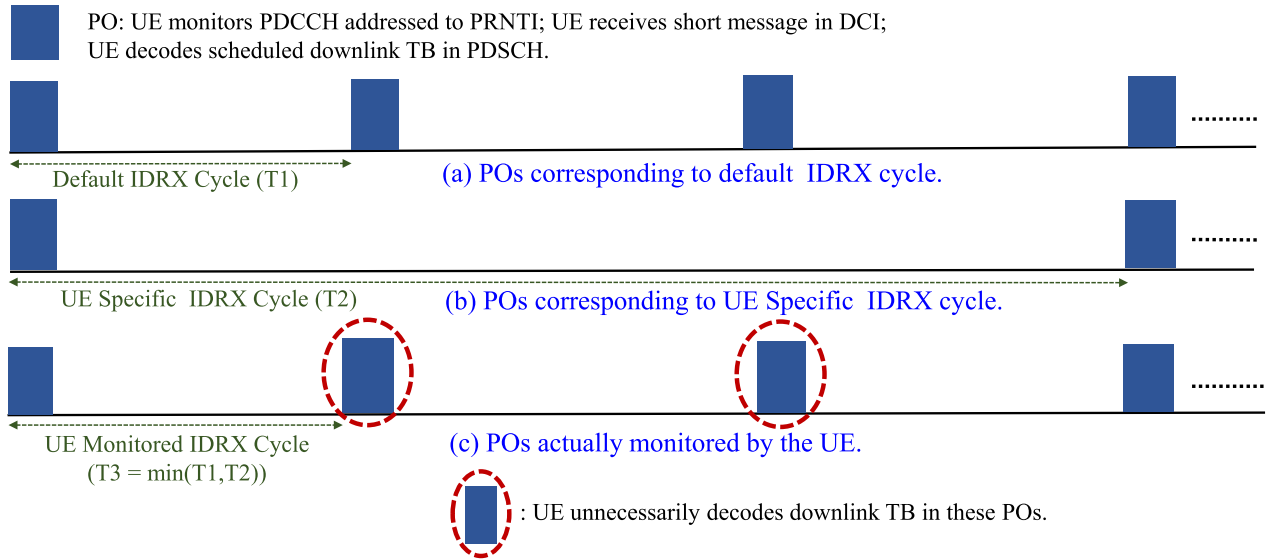


FIGURE 1. UE specific and default IDR cycle.

the POs of UE corresponding to UE specific IDR cycle when it is longer than default IDR cycle. Figure 1(c) shows the actual monitored IDR cycle according to the current specification [7]. When the UE specific IDR cycle is longer than the default IDR cycle, the frequent PO monitoring in every default IDR cycle leads to increased UE’s power consumption. On the other hand, monitoring PO every UE specific IDR cycle would result in UE missing the SI update and emergency notifications as these are transmitted in PO of default IDR cycle. In this paper, we investigate the aforesaid issue as it gets further elevated due to elaborate SSB measurements before a PO in 5G/B5G networks.

The UE’s IDR cycle in 5G and B5G communication is shown in Figure 2 (a). This figure is based on IDR cycle length being minimum of the default IDR cycle and UE specific IDR cycle and thus, we call this existing scheme as ‘MIN’ in this paper. The UE is required to measure SSBs before every PO in the IDR cycle in order to perform CFO (carrier frequency offset) compensation, automatic gain control and time/frequency tracking for Physical Downlink Shared Channel (PDSCH) and Physical Downlink Common Control Channel (PDCCH) reception in PO. These SSBs’ form an SS Burst that is periodically transmitted every 20 ms [8]. In the PO, UE receives scheduling information for PDSCH in PDCCH. UE receives paging message on PDSCH. PDSCH decoding is very sensitive to the time-frequency synchronization error unlike PDCCH and multiple SS burst measurements are required to decode the PDSCH with high reliability [9], [10]. Multiple SS burst measurements manifest reduced deep sleep duration in every IDR cycle. UE suffers higher power drains due to elaborate preparation time for PDSCH reception in PO compared to legacy networks. Furthermore, when UE specific IDR cycle is longer than default IDR cycle, the power saving further impedes as

UE is performing multiple SS burst measurements in every default IDR cycle which is shorter than its negotiated IDR cycle. To improve UE’s power saving in such scenarios, we propose a novel Enhanced UE specific Paging Monitoring (EPM) scheme. More precisely the contributions of this paper are as follows:

- We first delineate the details of IDR cycle in 5G/B5G networks. We specifically show that UE’s power consumption is substantially increased due to not only SSB measurements but also due to the intermediate light sleeps and power consumption in several transitions between light sleeps, deep sleep, measurements, monitoring and decoding.
- We propose an EPM scheme, in which we configure two types of PO monitoring. UE monitors paging message and short message in one type of PO and only short message in the other type. SI updates and emergency notifications are carried in short message. With two types of PO monitoring in EPM, the non essential SSB measurements and related overheads are avoided in several IDR cycles resulting in power saving. We analyse the advantages of EPM compared to existing system ‘MIN’ where UE performs multiple SSB measurements in every default IDR cycle.
- Subsequently, we extend our proposal by incorporating Paging Early Indication (PEI). PEI incorporates special wake up signal that UE monitors before the PO. PEI intimates UE about the presence or absence of paging message in the PO. If the PEI is present, UE proceeds with relevant SSB measurements and paging message reception in the PO. On the other hand, UE can transit to deep sleep by avoiding unnecessary processing if PEI is absent as it implies that there is no paging message in the upcoming PO. We apply UE specific paging

monitoring (EPM) scheme along with PEI to further improve UE's power saving.

- EPM manifests up to 37% more power saving than existing MIN approach. Even with the application of PEI, the power saving in EPM+PEI is substantially higher (10%) and (28%) than MIN+PEI for low and higher paging rate of 10% and 40%, respectively.

The rest of the paper is organized as follow: DRX background, need of SSB measurements and our methodology is presented in Section II. A survey of related work is presented in Section III. In Section IV we delineate the details of existing MIN system that provides fundamentals of IDRX in 5G and B5G networks. The proposed EPM approach is presented in Section V and is extended by including PEI in Section VI. Section VII shows the obtained results. Finally Section VIII concludes our paper. Table 1, gives the list of abbreviations used in the paper.

II. IDRX BACKGROUND AND SSB MEASUREMENTS

A UE is required to turn-on the radio transceiver for checking the arrival of packets from the base station. However, keeping the radio transceiver always 'ON' would consume high power. The DRX mechanism adopted in LTE/LTE-A resolves this issue by allowing a UE to switch between the active and sleep cycles to achieve power saving [11]. By turning off its receiver periodically the UE can reduce its power consumption in DRX mode [12]. DRX can be applied in two modes: The radio resource control (RRC) connected mode (CDRX) and the RRC idle mode (IDRX) [13]. CDRX comprises of a sleep period and a small 'On Duration Period' in which the UE wakes up to check for packets arrival [13]. On packet arrival UE starts the inactivity timer. If packet is received before the expiry of the inactivity timer, it is restarted. However, when the inactivity timer expires, UE first transits to short sleep and subsequently to long sleep after configured number of short sleep cycles. If there is no packet arrival for configured number of long sleep cycles, the network releases the RRC connection. Thus, UE transits to RRC-idle mode such that it can enjoy extended sleep in IDRX [14]. UE can transit to longer deep sleep in an IDRX cycle with only an occasional waking up in the PO. Paging message in PO helps in locating the idle mode UE such that the incoming call is redirected properly [15]. UE also receives SI, ETWS and CMAS notifications in a PO. UE negotiates IDRX length based on its power saving requirements. At the same time SI, ETWS and CMAS notifications are broadcasted in a default IDRX cycle. It is notable that the UE specific negotiated length may be different than default IDRX cycle length. In a PO, UE first monitors PDCCH for paging and then decodes PDSCH if it is paged.

In this article we mainly focus on above explained IDRX mechanism and paging while especially considering 5G/B5G networks. Though there are many works that have investigated the paging operation in UMTS evolution and LTE networks [16], [17], however, there has been very limited discussion on NR paging in the literature [18]. It is notable

TABLE 1. List all abbreviations.

Base Station	BS
Commercial Mobile Alerts	CMAS
Connected Mode DRX	CDRX
Discontinuous Reception	DRX
Downlink Control Information	DCI
Earthquake/Tsunami warnings	ETWS
Energy Efficiency	EE
Enhanced Paging Monitoring	EPM
Green Cloudlet Network	GCN
Idle mode Discontinuous Reception	IDRX
Mobile IoT Devices	MID
New Radio	NR
Packet Arrival Delay	PAD
Packet Loss Rate	PLR
Paging Early Indication	PEI
Paging Occasion	PO
Physical Broadcast Channel	PBCH
Physical Downlink Common Control Channel	PDCCH
Physical Downlink Shared Channel	PDSCH
Primary Synchronization Signal	PSS
Radio Resource Control	RRC
Secondary Synchronization Signal	SSS
Synchronization Signal Block	SSB
System Information	SI
Tera Hertz	THz
User Equipment	UE

that the study on IDRX is also being considered for beam based directional communication in 5G/B5G networks by 3GPP standardization body [19]. This special attention is required as the employment of high frequency carriers in 5G/B5G networks complicates the air interface and subsequently the IDRX mechanism. At high frequencies, the beam based communication becomes essential to overcome path and propagation losses resulting in directional air interface. The spatial coverage of each beam is limited, thus, a beam alignment should precedes any information exchange between UE and gNB (5G base station). 3GPP has specified the concept of SSBs in 5G such that Primary Synchronization Signal (PSS), Secondary Synchronization Signal (SSS) and Physical Broadcast Channel (PBCH) are all packed as a single block [8], [20]. SSB measurements are required for CFO compensation, automatic gain control and beam alignment. Multiple SSBs together form an SSB burst set that is periodically transmitted. By changing beam direction of an SSB in the SSB burst set beam alignment is manifested. In every IDRX cycle UE should first carry out SSB measurements for beam alignment so that it can receive PDCCH for paging. SSB measurements in turn reduce UE's sleep time in IDRX cycle and subsequently the power saving also reduces. It is notable that higher link directionality would be even more relevant in future wireless communication which has already started venturing into the Tera Hertz (THz) frequency range [36] and so the analysis of IDRX imbued with SSB measurements becomes even more relevant. Thus, in presented work, we specially address this challenge.

To understand the impediments of SSB measurements on power saving in IDRX cycle of 5G/B5G network, we follow

the following methodology: After explaining background and related work, (i) First in section IV, we explain the existing system. (ii) In the next section, we then propose, EPM, where we consider two types of PO monitoring. We perform numerical analysis of EPM to evaluate the power consumption in the proposed EPM. We also evaluate the power consumption in the existing system so that the advantages of EPM over the existing system can be ascertained. We then evaluate delay to understand the cost of power saving in EPM. (iii) In the subsequent section, we extend our work by considering PEI along with the proposed EPM mechanism. Numerical analysis of the same is also performed. To draw a fair comparison, we also evaluate the power consumption for the case when of an paging early indication is applied to the existing system. (iv) Finally, we present numerical results in the VII section. We would like to emphasise that this the first work that gives the effect of SSBs on power saving in 5G/B5G IDRX as well as PEI imbued IDRX while considering light sleep, deep sleep and well as transition energies.

III. RELATED WORK

Energy consumption has always been one of the primary concern in the design and operation of wireless communication systems [21]. There are several research works that have highlighted the Energy Efficiency (EE) in 5G wireless, especially from the network point of view. This is because the future ultra dense networks are expected to consist of a massive number of BSs that consume very high energy in the network [22], [23]. Optimal controlling of the Base Station's (BS's) power by manifesting switching between awake mode and sleep mode in Ultra Dense Network (UDN), the key enabler for future wireless networks, has been discussed in [24]. The BS selection is optimized based on constraints of the coverage of UEs, the capacity of BSs, and the data rates while considering EE as the main objective [24]. Green Cloudlet Network (GCNs) is proposed in [25]. Cloudlets are self-maintained tiny data centers. While green energy can fully satisfy energy demands by some cloudlets', others are dependent on on-grid power. A novel green-energy aware Avatar placement strategy is proposed to minimize the total power consumption in GCN [25]. Authors have investigated a novel method in [26] for allocation of paging frames only in certain radio frames so that the BS can experience longer sleep. In view of several small cells and macro cells expected in 5G and B5G UDNs, a practical and dynamic energy consumption control is proposed in [27] for power-saving modes in radio networks. Using graph-theory based methods, especially the weighted degree centrality, the authors determine the order at which BSs are inspected for power-off/on procedure [27]. By manifesting sleep mode for the low-loaded cells, an energy management framework is obtained that optimizes network's power consumption [27]. The power consumption at the BS along with the UEs capacity is also optimized in [28]. From UE's perspective, objectives like signaling bits, handover, power consumption linked to the data traffic and availability are considered [28]. For calculation

of power consumption in 5G network, by considering all the main elements including UEs, authors in [29] extend 3-state DRX model to 4-state and 5-state DRX model. The work considers elements pertaining to virtual base station and show power saving with respect to inactivity timer, short and long DRX cycles [29]. Masoudi *et al.* have presented innovative means to monitor and evaluate energy efficiency in 5G networks while considering Cloud-RAN in [30]. While the aforesaid literature mainly highlights EE from network point of view, in this article we present power saving in 5G/B5G from UE's point of view.

There are several research works focused on device's power saving in future networks using DRX mechanism, however, they mainly highlight ultra dense connectivity with MTC (Machine Type Communication) and IoT (Internet of Things) devices. One of the key directions for paging in such battery powered devices is Group-oriented paging [31]. Trade-off between paging and delay while considering group-based content delivery is presented in [31]. When considering the grouping of Mobile IoT Devices (MIDs), Packet Loss Rate (PLR) and Packet Arrival Delay (PAD) play an important an role [32]. Verma *et al.* have proposed a new mathematical model to estimate PLR and PAD that occur due to diversity in mobility pattern in [32]. Subsequently, an energy efficient grouping approach for MIDs is proposed. Various EE trade-offs in ultra dense connectivity are discussed in [33]. Authors have highlighted EE from a wide range of topics: (i) from network point of view like, Ultra-Dense HetNet (UDHetNet), self organising networks and cognitive and (ii) also from angle of NB-IoT (Narrow-Band IoT) and massive MTC devices. While these aforesaid parameters focus on CDRX and massive connectivity, the idle mode power saving of a UE is a different challenge. Analysis of EE from UE's point of view becomes even more challenging in future wireless systems operating at GHz and THz frequencies. These millimeter GHz and sub-millimeter THz frequencies manifest very low received signal levels and hence, the demand for highly directive antennas. This type of directional communication can compensate high signal attenuation at high frequencies caused mainly due to sever path and propagation loss. Strong atmospheric absorption also causes the signal attenuation and up to 15 dB/km is observed at 60 GHz, 120 GHz, 180 GHz bands [34], [35]. The signals at high frequencies along with high path loss suffer atmospheric absorption, directivity, sensitivity to blockage and narrow beamwidth, due to shorter wavelengths [36]. Authors in [37] believe that energy efficiency along with bandwidth efficiency are the essential metrics in selecting technologies for 5G/B5G.

We would especially like to highlight that to improve UE's power saving in 5G and B5G networks, researchers are considering several possibilities, such as power saving signal for discontinuous reception, secondary cell dormancy, cross-slot scheduling, wireless energy harvesting (EH) etc. [2], [38], [39]. In particular, research effort has been made towards the concept of Wake-up signal indication (WUS) for enhanced

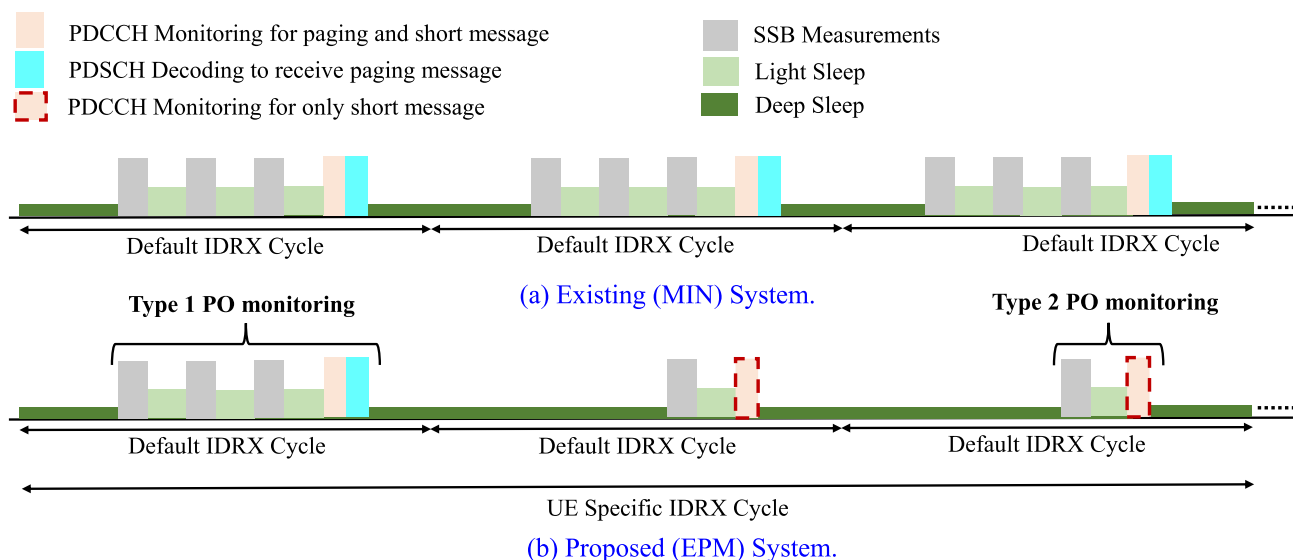


FIGURE 2. IDRX cycle with SSB measurements in 5G/B5G.

power saving in DRX mechanism. WUS is a narrow band signal that indicates the UE about arrival of packet. If the packet arrival is indicated by WUS only then the UE proceeds with PDCCH monitoring else it can continue to sleep [39], [40]. The concept of wake-up scheduling for the DRX mechanism is also discussed in [41]. Authors in [41] discuss offline and online modeling with optimization of wake up scheduler done for Poisson traffic and any traffic distribution respectively. However, the traffic model considered translates to a connected mode operation. CDRX for variable traffic scenarios is also considered [42] along with latency constraints. Pre-grant message: a narrow-band control plane signaling method is discussed for UE's EE improvement. Simulations on DRX with wake-up indications are performed in [2] and are compared to DRX without wake-up indication. Wake up indication in CDRX can substantially reduce (upto 33%) power consumption compared with the legacy DRX operation. However, it is notable that the existing works are focused on CDRX while the presented work in this article considers IDRX mechanism which to the best of our knowledge is not analysed in the literature yet. When in CDRX mode, the UE is connected to the eNB and thus, the parameters like inactivity timer, packet arrival, long and short sleep durations are important. Unlike these, in idle mode DRX the paging rate and paging arrival are important. Moreover, more than one UEs can be configured in the PO and all are required to observe paging in the PO if PDCCH for paging is received. It is notable that in IDRX UEs have longer opportunity to sleep resulting in higher power saving. Thus, we believe it is crucial to consider IDRX mechanism power saving in 5G/B5G networks. Since wake up signalling that manifests an early indication has shown potential power saving in CDRX, we have also extended our analysis by incorporating an early indication into IDRX mode that works with the proposed enhancements

to PO monitoring for 5G and B5G networks. Furthermore, as the use of high frequency carriers in 5G and B5G networks is a new paradigm, its impediments on the power saving of the UE in IDRX becomes important, especially since UE's EE is one of the major Key Performance Indicator (KPI's) in the future networks. To enable IDRX in beam based communication it is important to first perform SSB measurements so that the UE can recognize the best transmit beam in downlink for receiving PDCCH/PDSCH/WUS. Moreover, it should be done in an effective manner so that high power saving is achieved and thus is the fundamental motivation of our work.

IV. EXISTING SYSTEM

UE enjoys deep sleep in IDRX and only wakes up periodically in the PO where it first monitors PDCCH whose cyclic redundancy check is scrambled by Paging Radio Network Temporary Identifier (PRNTI) [7]. Subsequently, UE performs PDSCH decoding in the PO to receive paging message if scheduled by the PDCCH [4]. PDCCH carries Downlink Control Information (DCI). In case of SI update and emergency notifications, DCI includes short message. In case of paging, DCI includes information about the PDSCH resources for paging message. In other words, PDCCH is enough to receive the SI update and emergency notifications whereas PDSCH decoding becomes necessary only for paging message reception. However, the existing system do not take advantage of this differentiation. Even though, it is PDSCH decoding that essentially requires multiple SSB measurements but in the existing system UE performs these before every PO irrespective of whether paging message is scheduled or not. Furthermore, there are two possible IDRX cycle configurations (Default IDRX cycle and UE specific IDRX cycle) and elaborate SSB measurements are performed in both of them.

UE may negotiate a longer UE specific IDRX cycle for more power saving. UE monitors PO with respect to the minimum of the two IDRX cycles. Thus, even if UE specific IDRX cycle is longer than the default IDRX cycle, it is essentially required to decode PDSCH for paging message in PO of every default DRX cycle. The deep sleep time (see figure 2(a)) is significantly reduced due to multiple SSB measurements in every IDRX cycle of existing system. Moreover, UE transits to intermediate light sleeps between the multiple SSB measurements and the SSB measurement instance and the PO. UE also spends transition energy every time it transits to light sleep and deep sleep [19]. It is notable that the energy consumed in transition is substantially high [19]. When UE specific IDRX cycle is longer than default IDRX cycle in B5G, it may unnecessarily measure multiple SSBs, spend lot of energy on transitions and decode PDSCH for paging message in several POs. This is inessential as in default IDRX cycles UE is mainly looking for SI update and emergency notifications since it opted for longer IDRX cycle and thus, is not expecting paging. In our proposal, we aim to reduce these avoidable energy impediments. It may be argued that adhering to the default IDRX cycle can reduce paging latency as paging is monitored more frequently. However, the UE and network negotiated the UE specific paging IDRX cycle which implies that such frequent paging monitoring is not essential.

V. ENHANCED PO MONITORING (EPM)

In EPM, we propose two types of PO monitoring when the UE specific IDRX cycle length is longer than the default IDRX cycle:

- Type 1 PO monitoring: UE monitors PO for both paging message and short message
- Type 2 PO monitoring: UE monitors PO only for short message.

The longer UE specific IDRX cycle length is in multiple of default IDRX cycle length. In the first default IDRX cycle that occurs in the UE specific IDRX cycle, UE performs first type of PO monitoring. In the remaining, default IDRX cycles that occur within the UE specific IDRX cycle, UE performs second type of PO monitoring. While the former requires elaborate PO preparation for PDSCH decoding, the latter does not need multiple SSB measurements. With two types of PO monitoring in EPM, when the default IDRX cycle is shorter than the UE specific cycle, UE avoids inessential SSB measurements and related overheads in additional POs that are basically required for receiving short messages only. Thus, in EPM, UE has the flexibility to save more power by configuring longer UE specific IDRX cycle, while it can receive the necessary SI updates in short messages. More specifically, paging frame (PF) [14] where the UE monitors PO to receive paging or short message is determined as follows:

- 1) UE monitors PDCCH addressed to P-RNTI for the short message in the PO of the PF given by $(SFN + PFOffset) \bmod T_d = (T_d \div N) * (UEID \bmod N)$, where

SFN is the System Frame Number, PFOffset is the paging frame offset, N is the number of paging frames in an IDRX cycle and UEID is the user identifier. Since here UE is monitoring paging for the short message, we consider $T_d = DefaultDRXcycle$.

- 2) UE monitors PDCCH addressed to P-RNTI for the paging message in the PO of the PF given by $(SFN + PFOffset) \bmod T_u = (T_u \div N) * (UEID \bmod N)$, where $T_u = UEspecificDRXcycle$.

In Figure 2 we illustrate the PO monitoring in EPM in comparison to existing approach. A longer UE specific IDRX cycle is considered that consists of multiple default IDRX cycles. In EPM, UE monitors PO for paging message only once per UE specific IDRX cycle, that is, in one out of multiple default IDRX cycles as shown in figure 2. For this Type1 PO Monitoring, UE performs multiple SSB measurements and undergoes intermediate light sleeps as highlighted in Figure 2. In the remaining POs corresponding to default IDRX cycle that occur within the duration of the UE specific IDRX cycle, UE monitors only short message (Type2 PO Monitoring). However, as shown in Figure 2 multiple SSB measurements are not required for receiving short message. Thus, compared to existing approach the UE has more opportunity for deep sleep. The UE’s power consumption $PW1$ in EPM can be evaluated as

$$PW1 = \left[P_{SSB} * T_{SSB} * (N_{SSB} + K1 - 1) + P_{PO} * T_{PO} + P_{LS} * T_{LS} + P_{DS} * T_{DS} + (N_{SSB} + K1 - 1) * E_{LS} + K1 * E_{DS} \right] / T \tag{1}$$

where, the ratio K1 is defined as

$$K1 = \frac{UEspecificDRXcyclelength}{DefaultDRXcyclelength} \tag{2}$$

K1 gives the relation between UE specific and default IDRX cycle lengths. N_{SSB} is the number of times SSB measurements are conducted before the PO so that UE can reliably decode PDSCH. $(P_{SSB}, P_{PO}, P_{LS}, P_{DS})$ and $(T_{SSB}, T_{PO}, T_{LS}, T_{DS})$ are the power and time duration values respectively for SSB measurements, PO, light sleep and deep sleep. In IDRX, UE also spends energy in transition to light and deep sleep which is expressed as E_{LS} and E_{DS} , respectively. Considering T as the UE specific IDRX cycle length, we can calculate the time for deep and light sleeps as

$$T_{DS} = T - (N_{SSB} + K1 - 1) * T_{SSB} - T_{LS} - T_{PO} * K1 - (N_{SSB} + K1 - 1) * T_{LST} - K1 * T_{DST} \tag{3}$$

$$T_{LS} = (SSB_p - T_{SSB}) * N_{SSB} + (SSB_p - T_{SSB})(K1 - 1) - (N_{SSB} + K1 - 1) * T_{LST} \tag{4}$$

where, SSB_p is the duration of SS burst period the default setting for which is 20ms. T_{LST} and T_{DST} respectively are the transition time for light and deep sleep, such that $T_{DST} > T_{LST}$. These transition times are crucial as UE knows

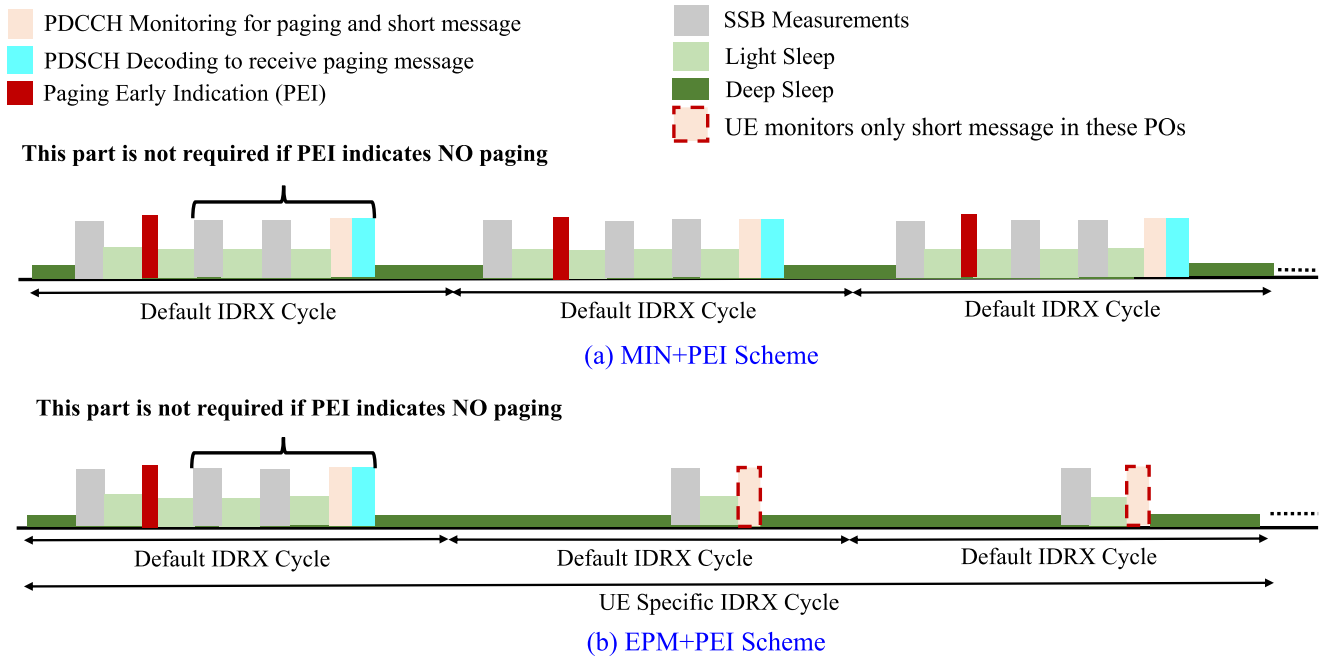


FIGURE 3. IDR cycle with SSB measurements and PEI in 5G/B5G.

that it should transits to light sleep when it does not expect to receive/ transmit for a while but the duration is not long enough for transition to the deep sleep [43]. In EPM, for longer UE specific IDRX, in one default IDRX cycle UE monitors PO for both PDCCH and PDSCH for paging message while in others it monitors PO for only PDCCH for short messages. If ρ is the paging rate then the power consumed in a PO can be evaluated as $P_{PO} = (\text{power consumption in first default IDRX cycle} + \text{power consumption in other default IDRX cycles})$. It can be expressed as

$$P_{PO} = (1 - \rho) * P_{PDCCH} + \rho * P_{PDSCH} + P_{PDCCH} * (K1 - 1) \quad (5)$$

where, P_{PDSCH} give the total power for PDSCH decoding + PDCCH monitoring and P_{PDCCH} gives the power for only PDCCH monitoring. It is important to note ρ is the paging rate for the PO (that is at least one UE is paged) and is not the UE's paging rate. Since many UE's can be configured in a PO depending upon the tracking area, the value of ρ could be reasonably high.

We also calculate the Power consumption $PW2$ in the existing system for comparison. We call the existing system approach as 'MIN' and $PW2$ is evaluated as

$$PW2 = \left[\left(P_{SSB} * T_{SSB} * N_{SSB} + P_{PO} * T_{PO} + P_{LS} * T_{LS} + P_{DS} * T_{DS} + N_{SSB} * E_{LS} + E_{DS} \right) * K1 \right] / T \quad (6)$$

However, for MIN approach, the P_{PO} , T_{LS} and T_{DS} are calculated as

$$P_{PO} = (1 - \rho) * P_{PDCCH} + \rho * P_{PDSCH} \quad (7)$$

$$T_{LS} = (SSB_p - T_{SSB}) * N_{SSB} - T_{LST} * N_{SSB} \quad (8)$$

$$T_{DS} = T - N_{SSB} * T_{SSB} - T_{LS} - T_{PO} - T_{LST} * N_{SSB} - T_{DST} \quad (9)$$

Using $PW1$ and $PW2$, we can calculate the percentage power reduction in proposed EPM compared to MIN approach. Since UE gets the opportunity to sleep for longer time, the arrival of paging for this particular UE under deep sleep would result in the delay. Though the UE itself negotiated a longer IDRX cycle which means it is not expecting paging, however, the wireless traffic is sporadic and the paging can arrive even when it was not expected by the UE. UE monitors paging in PO while the actual message can arrive anytime between the POs when UE is in deep sleep, measuring SSBs or is in light sleep. To calculate delay we consider the buffering time other than PO duration during which paging can arrive. The buffering time, similar to [44], [45], can be evaluated for existing system (Tb_{MIN}) and EPM (Tb_{EPM}) as

$$\Lambda_{MIN} = Tb_{MIN} - (1 - e^{-\Omega_a Tb_{MIN} / \Omega_a}) \quad (10)$$

$$\Lambda_{EPM} = Tb_{EPM} - (1 - e^{-\Omega_a Tb_{EPM} / \Omega_a}) \quad (11)$$

where, time lapse between monitored PO are given as Tb_{MIN} and Tb_{EPM} . From figure 2, $Tb_{MIN} = T$ and $Tb_{EPM} = (K1 * T)$ respectively. In EPM, UE monitors PO for paging only once every $K1$ default IDRX cycles, in other cycles it monitors only the short message and not paging. The delay

also depends upon the probability of UE's paging arrival rate Ω_a . We can calculate the average delay over time T_i for MIN and EPM respectively as $\Lambda_{MIN} * \omega_{MIN}$ and $\Lambda_{EPM} * \omega_{EPM}$. ω_{MIN} and ω_{EPM} are the probabilities of paging request in MIN and EPM respectively and can be computed as

$$\omega_{MIN} = \alpha \left(\frac{e^{-\Omega_a T b_{MIN}}}{1 - e^{-\Omega_a T b_{MIN}}} \right) \quad (12)$$

$$\omega_{EPM} = \beta \left(\frac{e^{-\Omega_a T b_{EPM}}}{1 - e^{-\Omega_a T b_{EPM}}} \right) \quad (13)$$

where $\alpha = (1 - e^{-\Omega_a T b_{MIN}}) (e^{-\Omega_a (T_i - T b_{MIN})})$ and $\beta = (1 - e^{-\Omega_a T b_{EPM}}) (e^{-\Omega_a (T_i - T b_{MIN} - (K1-1)T)})$.

VI. EPM WITH PAGING EARLY INDICATION

We extend our EPM proposal by incorporating PEI. PEI informs UE about absence or presence of the paging message in the PO before the actual PO instance so that unnecessary UE wake up is avoided and it is able to enjoy extended sleep. If PEI indicates that network has no paging for the UE in the upcoming PO, then UE does not perform multiple SSB measurements, several intermediate light sleeps, PDCCH monitoring and PDSCH decoding. Kindly note one SSB measurement would still be required for receiving PEI. On the other hand, the aforesaid operations for PO preparation and monitoring are performed only if PEI indicates the presence of paging message. PEI is an effective technique for power saving and by integrating PEI into the proposed EPM as shown in Figure 3, we can expect substantially higher power saving at the UE in B5G networks. Similar to Figure 2, for EPM+PEI in Figure 3, we consider a longer UE specific IDRX cycle such that it consists of multiple default IDRX cycles. When the PEI indicates paging message, while the scheme without EPM manifests elaborate PO preparation in every default IDRX cycle, the EPM+PEI is able to avoid the same in several default IDRX cycles by monitoring paging message only once per UE specific IDRX cycle. The IDRX cycle for short message in EPM+PEI gives more opportunity for sleep to the UE as shown in Figure 3. If, however, the PEI indicates no paging message then the IDRX cycle with or without EPM remains same. Thus, EPM+PEI would either perform better or equivalent to PEI based on the paging rate. The power consumption in the PEI integrated EPM approach with respect to paging rate can be evaluated as

$$PW3 = \left[(P_{SSB} * T_{SSB} * (N_{SSB} - 1) * \rho) + (P_{SSB} * T_{SSB} * K1) + P_{PEI} * T_{PEI} + P_{PO} * T_{PO} + P_{LS} * T_{LS} + P_{DS} * T_{DS} + (K1 + N_{SSB} * \rho) * E_{LS} + K1 * E_{DS} \right] / T \quad (14)$$

Here, we can assume T_{PEI} to have same length as T_{PO} . For EPM+PEI approach, the power consumption for PDSCH is limited to only first default cycle. The power consumption for $(K1-1)$ remaining default cycle includes only PDCCH power

in the P_{PO} . In EPM+PEI approach, P_{PO} , T_{LS} and T_{DS} are calculated as

$$P_{PO} = \rho * P_{PDSCH} + (K1 - 1) * P_{PDCCH} \quad (15)$$

$$T_{LS} = (SSB_p - T_{SSB}) * k1 + (SSB_p - T_{PEI}) * \rho - T_{LST} * K1 + (SSB_p - T_{SSB}) * (N_{SSB} - 1) * \rho - (N_{SSB} - 1) * \rho * T_{LST} \quad (16)$$

$$T_{DS} = T - T_{SSB} * k1 - ((N_{SSB} - 1) * T_{SSB} * \rho) - T_{LS} - T_{PO} * \rho - T_{PO} * (K1 - 1) - T_{PEI} - T_{LST} * K1 - (N_{SSB} - 1) * \rho * T_{LST} - T_{DST} * K1 \quad (17)$$

For fair comparison we also apply PEI to existing MIN approach. Power consumption in the existing MIN approach together with PEI can be evaluated as

$$PW3 = \left[(P_{SSB} * T_{SSB} + P_{SSB} * T_{SSB} * (N_{SSB} - 1) \rho) + P_{PEI} * T_{PEI} + P_{PO} * T_{PO} + P_{LS} * T_{LS} + P_{DS} * T_{DS} + (1 + N_{SSB} * \rho) * E_{LS} + E_{DS} * K1 \right] / T \quad (18)$$

In MIN+PEI, the PDSCH is decoded based on paging rate ρ . Thus, for this approach, P_{PO} , T_{LS} and T_{DS} are calculated as

$$P_{PO} = \rho * P_{PDSCH} \quad (19)$$

$$T_{LS} = (SSB_p - T_{SSB}) + (SSB_p - T_{PEI}) * \rho + (SSB_p - T_{SSB}) * (N_{SSB} - 1) * \rho - T_{LST} - N_{SSB} * \rho * T_{LST} \quad (20)$$

$$T_{DS} = T - T_{SSB} - (T_{SSB} * (N_{SSB} - 1) * \rho) - T_{LS} - T_{PO} * \rho - T_{PEI} - T_{LST} - N_{SSB} * \rho * T_{LST} - T_{DST} \quad (21)$$

Finally, we can calculate the percentage power reduction in EPM+PEI compared to MIN+PEI approach using PW3 and PW4. Similar to MIN and EPM, we can calculate the delay in MIN+PEI and EPM+PEI, from figure 3 by considering time lapse between monitored POs as $Tb_{MIN+PEI} = T$ and $Tb_{EPM+PEI} = K1 * T$ respectively. To calculate delay we consider the buffering time for MIN+PEI ($\Lambda_{MIN+PEI}$) and EPM+PEI ($\Lambda_{EPM+PEI}$) as

$$\Lambda_{MIN+PEI} = Tb_{MIN+PEI} - (1 - e^{-\Omega_a T b_{MIN+PEI}} / \Omega_a) \quad (22)$$

$$\Lambda_{EPM+PEI} = Tb_{EPM+PEI} - (1 - e^{-\Omega_a T b_{EPM+PEI}} / \Omega_a) \quad (23)$$

Thus, the average delay over time T_i for MIN+PEI and EPM+PEI can be evaluated respectively as $\Lambda_{MIN+PEI} * \omega_{MIN+PEI}$ and $\Lambda_{EPM+PEI} * \omega_{EPM+PEI}$, where, $\omega_{MIN+PEI}$ and $\omega_{EPM+PEI}$ are the probabilities of paging request and are calculated as

$$\omega_{MIN+PEI} = \gamma \left(\frac{e^{-\Omega_a T b_{MIN+PEI}}}{1 - e^{-\Omega_a T b_{MIN+PEI}}} \right) \quad (24)$$

$$\omega_{EPM+PEI} = \eta \left(\frac{e^{-\Omega_a T b_{EPM+PEI}}}{1 - e^{-\Omega_a T b_{EPM+PEI}}} \right) \quad (25)$$

where $\gamma = (1 - e^{-\Omega_a T b_{MIN+PEI}}) (e^{-\Omega_a (T_i - T b_{MIN+PEI})})$ and $\eta = (1 - e^{-\Omega_a T b_{EPM+PEI}}) (e^{-\Omega_a (T_i - T b_{EPM+PEI})})$.

Table 2 consolidates the key differences in MIN, EPM, MIN+PEI and EPM+PEI approaches.

VII. PERFORMANCE ANALYSIS

In order to check the effectiveness of the propose mechanism we present achieved power saving in EPM and EPM+PEI, while comparing it to the existing system as per 3GPP standards for 5G and call it as ‘MIN’. The power saving in EPM and EPM+PEI depend upon the following important factors:

- 1) Ratio of UE specific IDRX cycle length to the default IDRX cycle length (i.e. $K1$)
- 2) Number of SSB measurements required for receiving paging (N_{SSB})
- 3) The paging rate that gives number of times UEs are paged. It is notable that several UEs can be configured in a PO from the network’s point of view. If at least one of the configured UE’s is paged in a PO then all the configured UE’s must perform SSB measurements to receive paging.

Hence, in this section we delineate the analytical performance of EPM and EPM+PEI with respect to variations in $K1$, N_{SSB} and paging rate. The default IDRX cycle length in considers as $T = 320$ ms. Based on the signal quality before the reception of paging in the PO, the UE can select a maximum of three SSB burst measurements [10], [19] and thus, N_{SSB} is considered as either 1, 2 or 3. In our simulations, we have considered the SSB duration, T_{SSB} , ranging from 0.5 ms up to 5 ms. 0.5 ms is the lower limit for the case when there is no beamforming (i.e. only 1 SSB is transmitted by network). SSB burst duration scales as the number of beams increases with upper limit as 5 ms. T_{PO} is the duration for receiving PDCCH and PDSCH for paging corresponding to 1 SSB. One PDCCH and PDSCH can be received in 1 ms and so we have considered T_{PO} as 1 ms. Note that network transmits PDCCH and PDSCH for paging ‘N’ times, where N is the number of SSBs transmitted by network. However, UE needs to receive only one of these ‘N’ PDCCHs and PDSCHs based on SSB measurements before the PO. We consider $T_{LST} = 6$ ms. The light sleep duration can go up to 20 ms and $T_{DS} > 20$ ms. These values are based on 3GPP specifications. The power consumed in various operations as PDCCH/PDSCH/SSB processing, light/deep sleep, transitions, PEI measurements etc. are also considered in accordance with the 3GPP specifications and contributions [46]. The power parameters used are given in Table 3 which follows the scaling rule and power model in 3GPP’s TR38.840 [19]. It is to be noted that in EPM or EPM+PEI (from Fig.2 and 3), one SSB measurement along with related light sleep and transition is always needed either to measure paging message, short message or PEI.

In Figure 4, we consider two SSB measurements in a PO ($N_{SSB} = 2$) and show the power consumption for variation in $K1$ for the ratio 2, 4&8. Figure 4(a) compares power

consumption in EPM with the existing system (MIN) as highlighted in Figure 2 and Figure 4(b) compares EPM+PEI with MIN+PEI as illustrated in Figure 3. As expected, for the existing MIN system, even if UE negotiates longer IDRX cycle, still it is not able to save any power. However, in EPM, UE is able to conserve reasonable power even when the ratio $K1$ is just two. As the ratio increases the power saving becomes more substantial. If we consider $K1 = 1$, then the power consumption in both the EPM and MIN becomes same equal to 7.28, which also validates the accuracy of our model. In general, the power consumption while including PEI (Figure 4(b)) is lower than power consumption when PEI is not included (Figure 4(a)). It can be clearly seen that the power consumption in EPM+PEI is very low around 4.15 power units in each IDRX cycle compared to 6 in MIN and 4.45 in MIN+PEI for $K1 = 8$ and $N_{SSB} = 2$.

The power consumption as expected increases when $N_{SSB} = 3$ is considered as shown in Figure 5. The link quality in future wireless networks can not be expected to be robust due to spotty coverage at GHz and THz frequencies. Thus, $N_{SSB} = 3$ would not be uncommon. While Figure 5(a) considers comparison of EPM with MIN, figure 5(b) shows power consumption for EPM+PEI and MIN+PEI. The power consumption in MIN increases even more (to 7.4 power units) for $N_{SSB} = 3$ as in Figure 5(a). It is notable that power consumption in EPM is also increased to around 5.7 due to increase in SSB measurements and related overheads, however, for EPM+PEI the increase is very small, 4.18 power units. Thus, EPM with or without PEI can effectively save UE’s power. In Figure 4 and 5, we have assumed paging rate of 10%. In [10], authors have used 3GPP specification and have used Wake Up Signal (WUS) with paging message. For option 2 of the proposal in [10], the power saving gain in evaluated for the WUS duration of 2 ms and the relative power of 50. With paging rate of 10% and 20%, the power saving gain is obtained in the range of (21.6% to 29.2%) when WUS is applied to paging. In our proposal we have considered enhanced paging when UE’s negotiated IDRX cycle is different from default IDRX cycle. We propose PEI+EPM where the paging early indication is applied to EPM similar to WUS in [10]. From Figure 5, we can see that the power consumption of EPM+PEI (Figure 5(b)) is around 26% less when compared with EPM (Figure 5(a)) for small value of $K1 = 2$. This validates the accuracy of our proposal since the work in [10] has used similar 3GPP parameters as used in our proposal.

The effect of variation in paging rate over power consumption is delineated in Figure 6 (a). $K1$ is considered as 4 and $N_{SSB} = 3$ in Figure 6 (a). The effect of changing paging rate is very little on EPM and MIN schemes as they do not consider PEI. The power consumption in EPM and MIN remains almost same around 4.8 and 7.1. As the paging arrival rate increases, more POs indicate paging in PEI. Thus, as paging rate increases, both MIN+PEI and EPM+PEI show increase in power consumption. It is notable that performance of EPM even without PEI is much better than

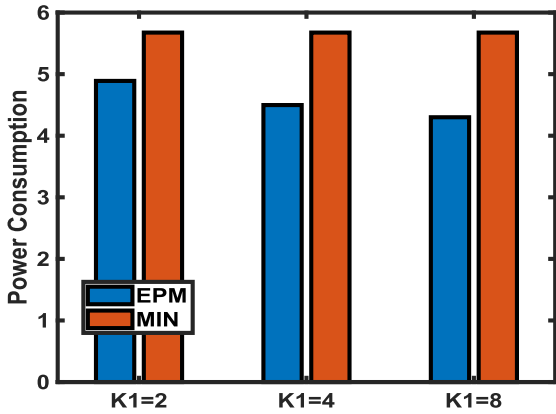
TABLE 2. Key differences in MIN, EPM, MIN+PEI and EPM+PEI.

	MIN	EPM	MIN + PEI	EPM + PEI
Length of UE specific IDRX cycle	$K1 * \text{Default IDRX cycle}$, where $K1 > 0$	$K1 * \text{Default IDRX cycle}$, where $K1 > 0$	$K1 * \text{Default IDRX cycle}$, where $K1 > 0$	$K1 * \text{Default IDRX cycle}$, where $K1 > 0$
SSB burst measurements	N_{SSB} measurements every default IDRX cycle	In first default IDRX cycle of UE specific DRX cycle, UE measures SS bursts. In other default DRX cycle(s) of UE specific DRX cycle, UE measures one SS burst.	For each default IDRX cycle of UE specific IDRX cycle: If PEI is received in a default IDRX cycle, UE measures N_{SSB} SS bursts. If PEI isn't received in a default IDRX cycle, UE performs only one SS burst measurement.	In first default IDRX cycle of UE specific DRX cycle: If PEI is received, UE measures N_{SSB} SS bursts. If PEI isn't received, UE measures only one SS burst. In other default IDRX cycle(s) of UE specific IDRX cycle: UE measures one SS burst.
Short message monitoring	Monitors for short message in every default IDRX cycle	Monitors for short message in every default IDRX cycle	Monitors for short message in every default IDRX cycle	Monitors for short message in every default IDRX cycle
Paging message monitoring	Monitors for paging message in every default IDRX cycle	Monitors for paging message in only first default IDRX cycle of UE specific IDRX cycle	Monitors for paging message in every default IDRX cycle of UE specific IDRX cycle	Monitors for paging message in only first default IDRX cycle of UE specific IDRX cycle
PEI monitoring	Not applicable	Not applicable	Monitors for PEI in every default IDRX cycle of UE specific IDRX cycle	Monitors for PEI in only first default IDRX cycle of UE specific IDRX cycle
Number of LS transitions	NSSB transitions every default IDRX cycle	NSSB transitions in first default IDRX cycle of UE specific IDRX cycle One transition in other default IDRX cycle(s) of UE specific IDRX cycle	$1+(N_{SSB} * \rho)$ transitions in every default IDRX cycle of UE specific IDRX cycle	$1+(N_{SSB} * \rho)$ transitions in first default DRX cycle of UE specific IDRX cycle. One transition in other default IDRX cycle(s) of UE specific IDRX cycle

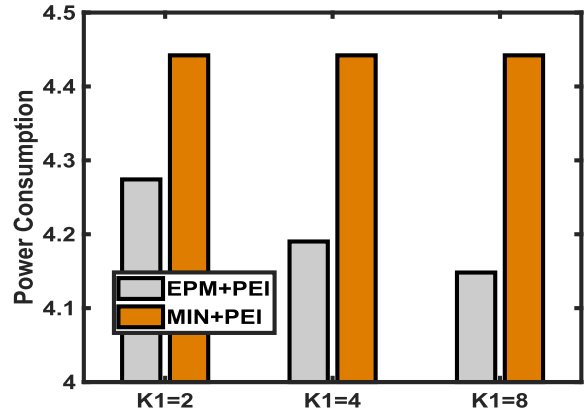
MIN+PEI as the paging rate increases. The performance of EPM+PEI as expected is better than all other possibilities. More importantly the effect of increase in paging rate is less on EPM+PEI. This is because even though the paging rate increases, the number of time the SSBs are elaborately measured would be less due to longer UE specified IDRX cycle. In Figure 6(b), the percentage power saving is delineated with respect to paging rate. For the fair comparison, percentage power saving in EPM is based on MIN scheme and EPM+PEI is based on MIN+PEI scheme. EPM can manifest around 30%–35% power saving for $N_{SSB} = 3$ and is almost independent of the paging rate. The percentage power saving in EPM+PEI increases compared to MIN+PEI as the paging rate increases. Though PEI is a promising technique in itself for power saving but its advantage reduces as the paging

rate increases. EPM+PEI can manifest more than 25% power saving compared to MIN+PEI, when paging rate in 40%.

The advantages of power saving is achieved at the cost of delay. It is notable that UE's negotiated longer IDRX cycle length which translates to UE not expecting any paging for itself. However, in case if this particular UE is paged at the arrival rate of Ω_a , then the arrived message can be processed only in the next monitored PO which would result in delay. In Figure 7(a), we show the effect of delay on EPM and in Figure 7(b) on EPM+PEI. As expected when the arrival rate increases the delay increases. Moreover, when $K1$ is increased the delay increases. This is because the UE is monitoring POs for paging less often (once in two default cycles in Figure 7(a) and once in 4 default cycles in Figure 7(b)) in EPM and EPM+PEI. The delay in case of MIN and

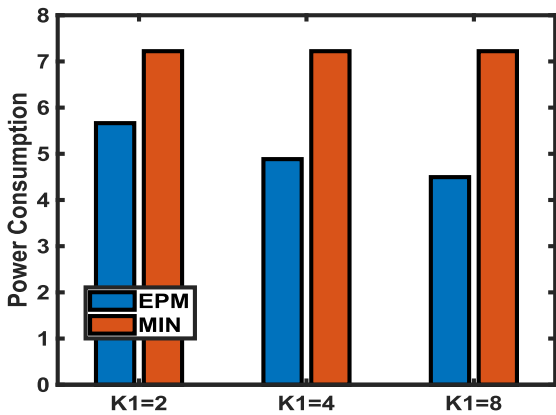


(a) EPM and MIN.

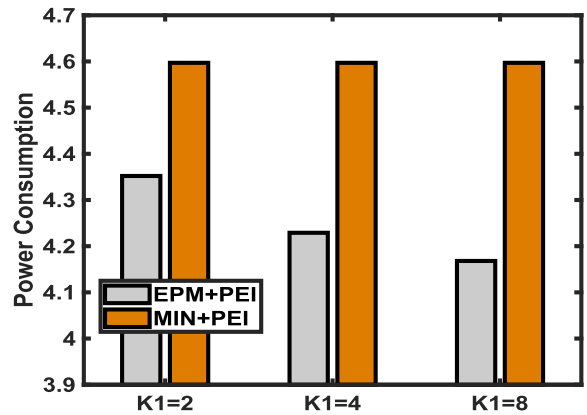


(b) EPM+PEI and MIN+PEI.

FIGURE 4. Power consumption for $N_{SSB} = 2$.

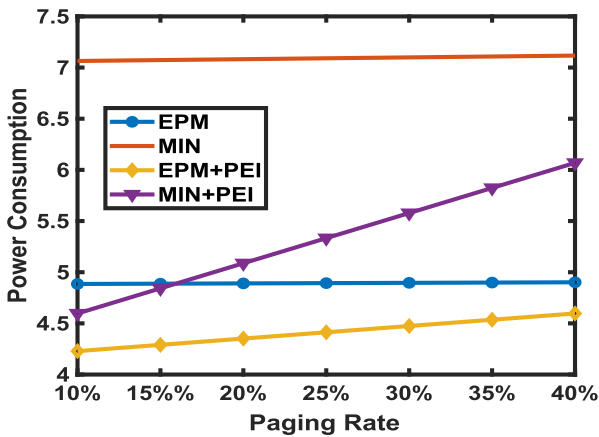


(a) EPM and MIN.

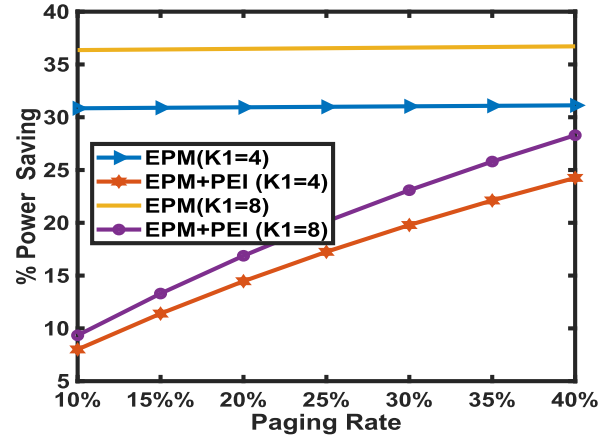


(b) EPM+PEI and MIN+PEI.

FIGURE 5. Power consumption for $N_{SSB} = 3$.



(a) Power Consumption v/s ρ ($N_{SSB} = 3, K1 = 4$).

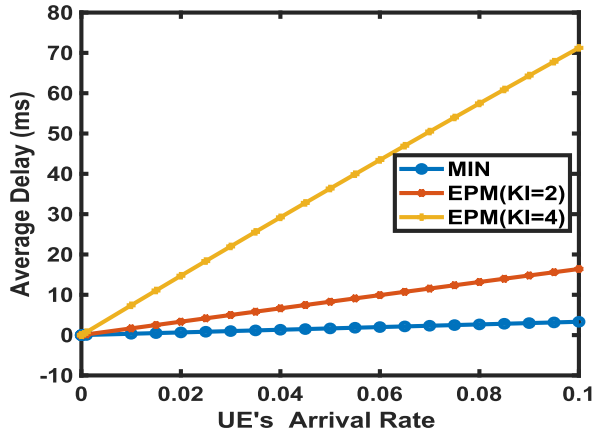


(b) % Power Saving w.r.t MIN and MIN+PEI v/s ρ

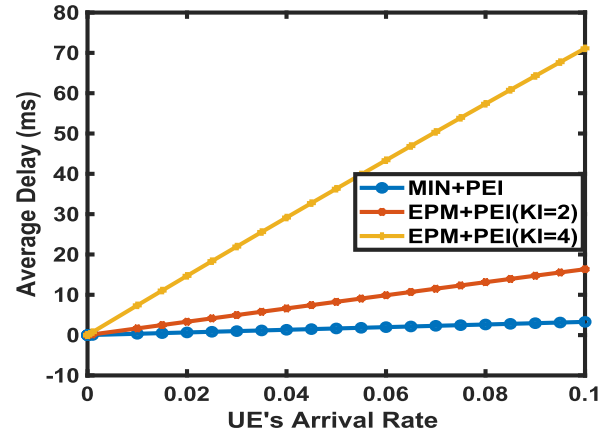
FIGURE 6. Varying paging rate.

MIN+PEI increase only slightly with the arrival rate. Thus, the power saving in EPM and EPM+PEI is obtained at the cost of delay. Moreover, as seen in Figure 7, the effect of PEI on delay is negligible as in default cycles UE is

anyway not monitoring any paging early indication. Finally, in Figure 8, we show the effect on power saving with the increase in number of beams. More number of beams mean that UE has to perform SSB measurement for longer duration.

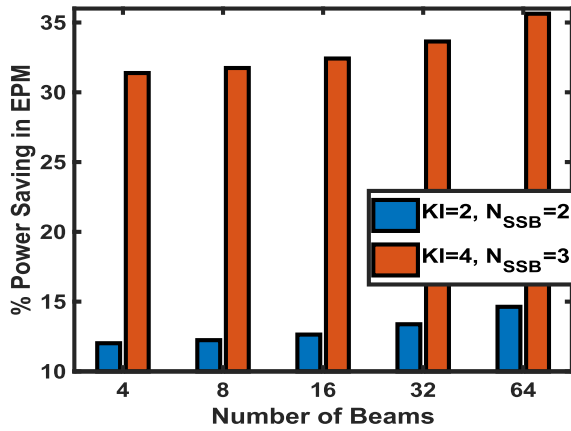


(a) Delay v/s UE's paging arrival.

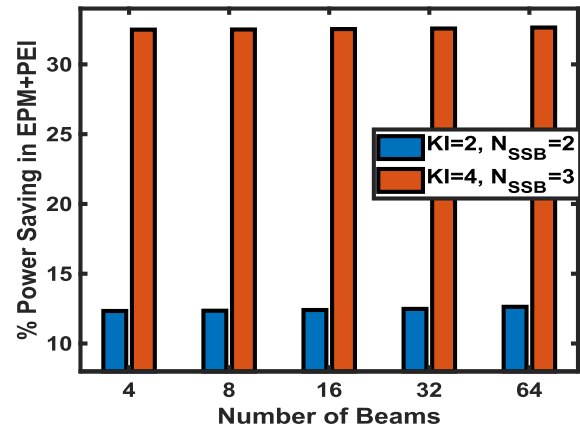


(b) Delay v/s UE's paging arrival when PEI is considered

FIGURE 7. Varying UE's arrival rate, $N_{SSB} = 3, KI = 4$.



(a) % Power Saving in EPM with varying Number of Beams.



(b) % Power Saving in EPM+PEI with varying Number of Beams.

FIGURE 8. Varying number of beams.

TABLE 3. Power parameters used.

Power State	Relative Power (Compared to DS)
PDCCH Processing, P_{PDCCH}	50
PDCCH+PDSCH Processing, P_{PDSCH}	120
SSB Processing, P_{SSB}	50
Light Sleep, P_{LS}	20
Deep Sleep, P_{DS}	1
PEI, P_{PEI}	50
Energy in light Sleep transition, E_{LS}	100
Energy in light Sleep transition, E_{DS}	450

Thus, as the number of beams increase, the power saving increases in Figure 8(a) because UE is performing SSB measurements less often in EPM compared to MIN. In Figure 8 (b), we have considered the paging arrival rate

of 10%. If PEI is considered, the UE anyway is able to avoid SSB measurements in MIN system as well whenever PEI indicates absence of paging. Thus, the power saving in Figure 8(b) is almost similar with the change in the number of beams and EPM+PEI gives consistent results.

VIII. CONCLUSION

High-frequency and less-congested spectrum bands such as the millimeter wave (mmWave) bands (30 to 300 GHz) promise solution for an ever increasing network capacity demands. There is a growing interest in utilization of these bands for 5G and B5G communications. The radio emission fields at these frequencies are considerably different from the legacy 4G generation mobile radio systems. This is mainly because of the complex beamformed transmissions, which requires SSB measurements for beam alignment between UE and BS. While Idle mode-Discontinuous Reception (IDRX) is an effective mechanism for UE's power saving, it becomes more complicated in such 5G and B5G networks. The deep sleep time manifested in every IDRX cycle reduces due to

long PO (Paging Occasion) preparation for SSBs measurements. A UE can negotiate longer IDRX cycle length for more power saving. However, it has to monitor POs in default IDRX cycle length broadcasted by the network to receive system information (SI) and emergency notifications (EN). We propose a novel enhanced paging monitoring (EPM) scheme so that UE can avoid inessential SSB measurements when it configures longer UE specific IDRX cycles by manifest two types of PO monitoring. We further extend our proposal by incorporating paging early indication (PEI) into EPM. The power saving in EPM and EPM with PEI is substantially higher (25 -30%) than existing system with or without PEI respectively. While EPM is one of the methods that can improve UE's power saving, the SSB imbued IDRX can further be explored for variable SSB measurements based on signal strength for even more power saving at the UE. Moreover, the concept of paging early indication can be extended by using machine learning tools to predict the paging arrival in a particular PO, so that UE can enjoy much longer deep sleeps when paging is not predicted. For our future work we plan to extend the EPM proposal by incorporating variable SSB measurements. Furthermore, we plan to map these SSB measurements to the signal strength. The incorporation of SSB measurements to IDRX cycle offers several novel research challenges that can be further explored.

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