Fayoum University Faculty of Engineering, 2024, Vol: 7(2), 67-81
https://fuje.journals.ekb.eg/
ISSN Online: 2537-0634
ISSN Print: 2537-0626

Performance Comparison of External Active States for LTE DRX and HD-DRX Scenarios Based on Semi-Markov in 4G and 5G Networks

Mustafa M. Sallam [1*], Mohamed Hassan M. Mahmoud [1]

[1,2]Communications and Electronics Department, Giza Higher Institute for Engineering and Technology, Giza, Egypt

*Corresponding author: Mustafa Sallam A. Author (Mustafa.Sallam@gei.edu.eg).

How to cite this paper: Sallam, M.M. & Mahmoud, M.H.M. (2024). Performance Comparison of External Active States for LTE DRX and HD-DRX Scenarios Based on Semi-Markov in 4G and 5G Networks. *Journal of Fayoum University Faculty of Engineering, Selected papers from the Third International Conference on Advanced Engineering Technologies for Sustainable Development ICAETSD, held on 21-22 November 2023, 7(2)*, 67-81.
https://dx.doi.org/10.21608/fuje.2024.343766

Abstract

Energy consumption is one of the most vital obstacles which face wireless mobile communications to satisfy the User Equipment (UE) with great multimedia services. Unfortunately, the UE battery energy is more absorbed with higher users' requirements. The Discontinuous Reception (DRX) sleep mode is introduced as an energy saving mechanism to turn off the UE radio transceiver circuit when no traffic arrival is indicated from the Base Station (BS). DRX sleep mode can be operated in the Fourth Generation Long Term Evolution (4G LTE) and the Fifth Generation New Radio (5G NR) networks. In 4G LTE DRX networks, the original model is defined as LTE DRX (3-states). In 5G NR networks, the original model is defined as Hybrid Directional-DRX (HD-DRX (4-states)). To enhance the performance, external active states are added to each DRX cycle of the original models. Adding only one active state to the DRX short cycle produces the extended LTE DRX (4-states) and HD-DRX (5-states) models while adding another active state to the DRX long cycle, in addition to the added one to the DRX short cycle, produces the extended LTE DRX (5-states) and HD-DRX (6-states) models. A Semi-Markov chain model is used to describe the UE transition states based on the light traffic threshold value. In this paper, the performance of each extended model is evaluated compared to its original model. Since energy saving and delay are highly trade-offs, the power saving factor and the average delay are the best common metrics to be measured. The extended LTE DRX models enhance the power saving factor by about (0.1 – 9) % compared to that of the original LTE DRX model. The extended HD-DRX models enhance the power saving factor by about (0.2 – 10) % compared to that of the original HD-DRX model. In spite of beam searching process, the extended HD-DRX models reduce the average delay by about (8 – 6000) msec compared to that of the original HD-DRX model. At the end of this paper, there is another performance comparison between the LTE DRX and HD-DRX extended models scenarios.

Keywords

LTE DRX; HD-DRX; Original Model; Extended Model; Active States; Power Saving Factor; Average Delay; States

1. Introduction

Nowadays, modern User Equipment (UE) terminals are satisfied with great multimedia services such as Internet applications which require higher data transmission rate [1-3]. The higher data transmission rate, the higher Signal-to-Noise Ratio (SNR) is required by the UE. Thus, the Base Station (BS) will allocate a huge number of physical Radio Resource Blocks (RRB_s) to the UEs which own a higher SNR [4-6]. Consequently, the UE_s consume much energy from their battery charge. To overcome this issue, Discontinuous Reception (DRX) sleep mode is introduced in [7-10] as an energy saving mechanism to enable an idle UE when no traffic arrival is indicated from the BS. Traditionally, DRX sleep mode was proposed in the Fourth Generation Long Term Evolution (4G LTE) networks. Recently, it is developed in the Fifth Generation New Radio (5G NR) networks by the Third Generation Partnership Project (3GPP) [11]. In 4G LTE networks, the LTE DRX scenario is presented with UE transition states defined as active state, light sleep state and deep sleep state [12]. In 5G NR networks, the Hybrid Directional-DRX scenario is also presented with UE transition states defined as active state, light sleep state, beam searching state and deep sleep state [13,14]. Active state has an inactivity timer which starts with traffic arrival indication and the sleep states have DRX short cycle and DRX long cycle timers [7-14].

In [12] and [13], LTE DRX and HD-DRX scenarios were proposed as original models defined as LTE DRX (3-states) and HD-DRX (4-states) respectively. External active states of each DRX cycle are being discussed to enhance the performance. This idea was firstly introduced for LTE DRX scenario in [15]. This paper introduces the external active states of each DRX cycle for HD-DRX scenario. By adding only one active state to the DRX short cycle of the original LTE DRX (3-states) and HD-DRX (4-states) models, the extended LTE DRX (4-states) and HD-DRX (5-states) models are resulted. By adding another active state to the DRX long cycle, in addition to the added one to the DRX short cycle, the extended LTE DRX (5-states) and HD-DRX (6-states) models are resulted. A Semi-Markov chain model is also used to describe the UE transition states based on the light traffic threshold value of extended models for both LTE DRX and HD-DRX scenarios. When the traffic arrival weight is greater than the light traffic threshold value, the UE leaves from DRX short/long cycle to the active state or beam searching state for LTE DRX and HD-DRX scenarios, respectively. Otherwise, the UE leaves from DRX short/long cycle to the extended active state. However the external active states have the same ON duration, the extended models improve the performance compared to the original models. To assign a performance comparison, the power saving factor and the average delay are very essential to be obtained. For LTE DRX scenario, power saving factor is enough as delay can be ignored due to no beam searching process [16]. For HD-DRX scenario, both power saving factor and average delay are estimated due to beam searching process [13,14]. It is better to be mentioned that power saving and delay are highly trade-offs [6]. This paper can be organized as follows: Section 1 introduces the paper, Section 2 describes the system model and provides the mathematical analysis, Section 3 observes the analytical results and discussions and Section 4 concludes the paper.

2. System Model and Mathematical Analysis

2.1. System Model

According to traffic which arrives within the ON periods of each DRX cycle, the UE can measure the traffic weight to determine if it is heavy or light based on the light traffic threshold value [15]. If traffic arrival weight is greater than the light traffic threshold value, the traffic is considered as "Heavy". Otherwise, it is considered as "Light". A Semi-Markov chain model is recommended to describe the UE transition states based on probabilistic values [7-16]. There are two scenarios which draw these transition states. The first scenario is called LTE DRX and the second scenario is called HD-DRX. For LTE DRX scenario, the UE has three separated transition states as follows: active state (i.e. inactivity timer), light sleep state (i.e. DRX short cycle timer) and deep sleep state (i.e. DRX long cycle timer). For HD-DRX scenario, the UE has four separated transition states as follows: active state, light sleep state, beam searching state and deep sleep state with the same DRX timers of LTE DRX scenario. It is noticeable that the beam searching state is the unique different state between the both scenarios. Consequently, the original models of both scenarios are defined as LTE DRX (3-states) and HD-DRX (4-states). External active states to the original model are translated into adding active states to each DRX cycle. When only one active state is added to the DRX short cycle, extended LTE DRX (4-states) and extended HD-DRX (5-states) models are produced. When another active state is added to the DRX long cycle, in addition to the added one to the DRX short cycle, extended LTE DRX (5-states) and extended HD-DRX (6-states) models are produced. With the aid of block diagram, Figure 1 illustrates the system model.

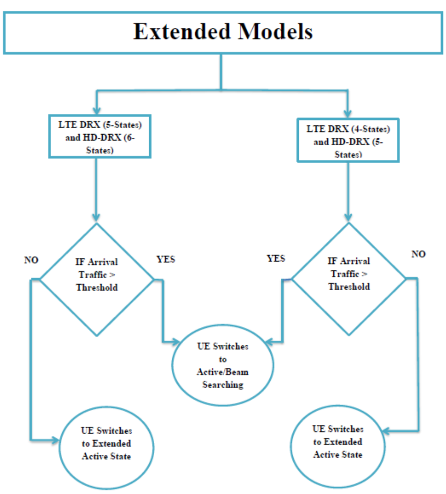
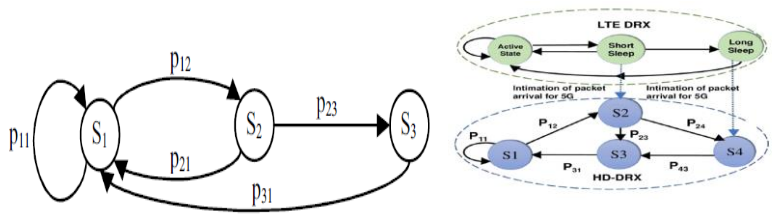


Figure 1. External Active States System Model

2.1. Mathematical Analysis

Based on the memory less property of the Semi-Markov chain model [7-16], the UE transition states probabilities are derived for both LTE DRX and HD-DRX scenarios. The original LTE DRX (3-states) and the original HD-DRX (4-states) models are described in Figure 2(a) and Figure 2(b), respectively. Table 1 contains the definitions of all parameters appear in the mathematical analysis. The mathematical analysis of external active states to the original model can be divided into two other sub-sections as follows:



(a) LTE DRX (3-states) Model

(b) HD-DRX (4-states) Model

Figure 2. Original Models Based on Semi-Markov Chain [13,14]

2.2.1. LTE DRX Scenario Mathematical Analysis

Figure 3 shows the extended LTE DRX (4-states) system model drawn by using of the Semi-Markov chain model. This extended model is derived from adding only one active state to the DRX short cycle of the original model. Four UE transition states of the extended LTE DRX (4-states) model are defined as the following: active state, light sleep state, deep sleep state and external active state to the DRX short cycle state represented by $\mathbf{S_1}$, $\mathbf{S_2}$, $\mathbf{S_3}$ and $\mathbf{S_4}$ respectively.

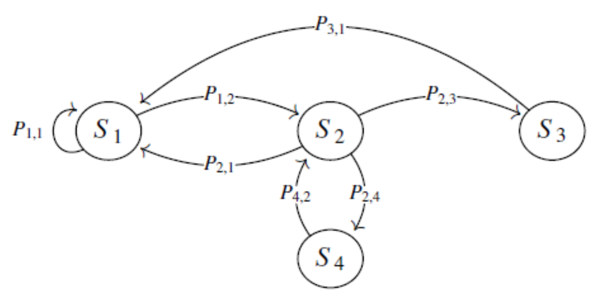


Figure 3. Extended LTE DRX (4-states) Model Based on Semi-Markov Chain [15]

A packet call may arrive during S_1 before the inactivity timer t_I is expired, the UE goes back to the same state S_1 given as follows [12-16]:

$$p_{11} = P_{pc}(1 - e^{-\lambda_{ipc}t_I}) + P_s(1 - e^{-\lambda_{is}t_I}) \quad (1)$$

Where ($t_{ipc} < t_I$ and $t_{is} < t_I$)

Note that: $P_{pc} = 1 - {}^{1}/_{\mu_{pc}}$ and $P_s = {}^{1}/_{\mu_{pc}}$ where P_{pc} is a packet call arrival probability during the current session and P_s is a new session arrival probability.

Otherwise, the UE leaves to the light sleep state S_2 given as follows [12-16]:

$$p_{12} = P_{pc}e^{-\lambda_{ipc}t_I} + P_s\ e^{-\lambda_{is}t_I} \quad (2)$$

Where ($t_{ipc} > t_I$ and $t_{is} > t_I$)

When the UE is indicated with a traffic arrival during the ON duration (t_{ON}) of each DRX short cycle t_{sc} in the light sleep state S_2, the UE measures the arrival traffic weight compared to the short light traffic threshold value LT_{short}. If the measured weight is greater than LT_{short}, the UE leaves the light sleep state S_2 to the active state S_1 with a transition probability p_{21} given as follows [15]:

$$p_{21} = P_{pc}(1 - e^{-\lambda_{ipc}t_N})^{LT_{short}+1} + P_s(1 - e^{-\lambda_{is}t_N})^{LT_{short}+1} \quad (3)$$

Otherwise, the UE leaves the light sleep state S_2 to the external active state to the DRX short cycle S_4 with a transition probability p_{24} given as follows [15]:

$$p_{24} = 1 - p_{21} - p_{23} \quad (4)$$

At S_4 state, the UE can't detect any path except from S_4 to S_2. Therefore, the UE leaves the external active state S_4 to the light sleep state S_2 with a transition probability p_{42} given as follows [15]:

$$p_{42} = 1 \quad (5)$$

At S_2 state, if no traffic arrival until DRX short cycle timer t_N is expired, the UE leaves the light sleep state S_2 to the deep sleep state S_3 with a transition probability p_{23} given as follows [12-16]:

$$p_{23} = P_{pc}\ e^{-\lambda_{ipc}t_N} + P_s\ e^{-\lambda_{is}t_N} \quad (6)$$

At S_3 state, the UE sleeps for each DRX long cycle t_{lc} until it wakes up during the ON duration t_{ON} or DRX long cycle t_{lc} is expired. Whether this or that, the UE leaves the deep sleep state S_3 to the active state S_1 with a transition probability p_{31} given as follows:

$$p_{31} = 1 \quad (7)$$

The UE mean holding time $E[H_1]$ at the active state S_1 is expressed as follows [12-16]:

$$E[H_1] = \left(\frac{\mu_p - 1}{\lambda_p}\right) + \left(\frac{P_{pc}}{\lambda_{ipc}}\right)(1 - e^{-\lambda_{ipc}t_I}) + \left(\frac{P_s}{\lambda_{is}}\right)(1 - e^{-\lambda_{is}t_I}) \quad (8)$$

The UE mean holding time $E[H_2]$ at the light sleep state S_2 is also expressed as follows [15]:

$$E[H_2] = (p_{23}(N_{sc} + LT_{short}) + p_{21}E[N_{sc}^{**}] + p_{24}E[N_{sc}^{*}])(t_{sc} - t_{ON}) \quad (9)$$

The mean value of N_{sc}^{*} is derived as follows [12-16]:

$$E[N_{sc}^{*}] = P_{pc}\left[\frac{1 - e^{-\lambda_{ipc} N_{sc} t_{sc}}}{1 - e^{-\lambda_{ipc} t_{sc}}} - N_{sc}e^{-\lambda_{ipc} N_{sc} t_{sc}}\right] + P_s\left[\frac{1 - e^{-\lambda_{is} N_{sc} t_{sc}}}{1 - e^{-\lambda_{is} t_{sc}}} - N_{sc}e^{-\lambda_{is} N_{sc} t_{sc}}\right] \quad (10)$$

The mean value of N_{sc}^{**} is derived as follows [15]:

$$E[N_{sc}^{**}] = \frac{P_{pc}}{1 - e^{-\lambda_{ipc} t_N \left(\frac{LT_{short}+1}{LT_{short}+N_{sc}}\right)}} + \frac{P_s}{1 - e^{-\lambda_{is} t_N \left(\frac{LT_{short}+1}{LT_{short}+N_{sc}}\right)}} \quad \textbf{(11)}$$

The UE mean holding time $E[H_3]$ at the deep sleep state S_3 is expressed as follows [12-16]:

$$E[H_3] = \left[\frac{P_{pc}}{1 - e^{-\lambda_{ipc}\, t_{lc}}} + \frac{P_s}{1 - e^{-\lambda_{is}\, t_{lc}}}\right](t_{lc} - t_{ON}) \quad \textbf{(12)}$$

The UE mean holding time $E[H_4]$ at the external active state to the DRX short cycle S_4 can be expressed as follows [12-16]:

$$E[H_4] = (p_{42} E[N_{sc}^{*}]) t_{ON} \quad \textbf{(13)}$$

Figure 4 shows the extended LTE DRX (5-states) system model drawn by using of the Semi-Markov chain model. This extended model is derived from adding another active state to the DRX long cycle of the original model, in addition to the added one to the DRX short cycle. Five UE transition states of the extended LTE DRX (5-states) model are defined as the following: active state, light sleep state, deep sleep state, external active state to the DRX short cycle state and external active state to the DRX long cycle state represented by S_1, S_2, S_3, S_4 and S_5

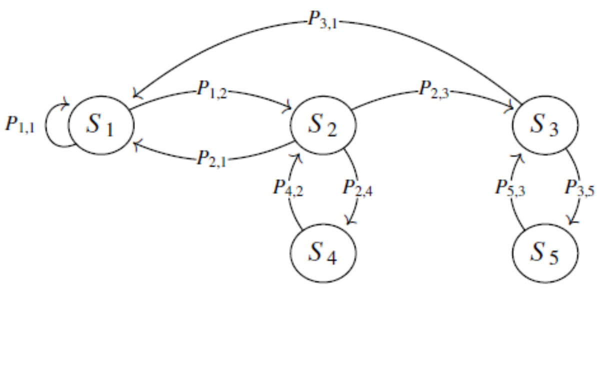


Figure 4. Extended LTE DRX (5-states) Model Based on Semi-Markov Chain [15]

When the UE is indicated with a traffic arrival during the ON duration (t_{ON}) of each DRX long cycle t_{lc} in the deep sleep state S_3, the UE measures the arrival traffic weight compared to the long light traffic threshold value LT_{long}. If the measured weight is greater than LT_{long}, the UE leaves the deep sleep state S_3 to the active state S_1 with a transition probability p_{31} given as follows [15]:

$$p_{31} = P_{pc}\left(1 - e^{-\lambda_{ipc} t_{lc}}\right)^{LT_{long}+1} + P_s\left(1 - e^{-\lambda_{is} t_{lc}}\right)^{LT_{long}+1} \quad \textbf{(14)}$$

Otherwise, the UE leaves the deep sleep state S_3 to the external active state S_5 with a transition probability p_{35} given as follows [15]:

$$p_{35} = 1 - p_{31} \quad \textbf{(15)}$$

At S_5 state, the UE can't detect any path except the path from the external active state S_5 to the deep sleep state S_3 with a p_{53} transition probability given as follows [15]:

$$p_{53} = 1 \quad \textbf{(16)}$$

Note that the transition probabilities p_{11}, p_{12}, p_{21}, p_{24}, p_{42} and p_{23} are the same as expressed by equations (1), (2), (3), (4), (5) and (6) respectively. Consequently, $E[H_1]$, $E[H_2]$ and $E[H_4]$ are the same as expressed by equations (8), (9) and (13) respectively.

While the UE mean holding time $E[H_3]$ at the deep sleep state S_3 is given as follows [15]:

$$E[H_3] = (p_{35} E[N_{lc}^{*}] + p_{31} E[N_{lc}])(t_{lc} - t_{ON}) \quad \textbf{(17)}$$

The mean value of $E[N_{lc}]$ is given in [12-16] while the mean value of N_{lc}^{*} can be derived as follows [15]:

$$E[N_{lc}^{*}] = \frac{P_{pc}}{1 - e^{-\lambda_{ipc} t_{lc}\left(\frac{LT_{long}}{LT_{long}+1}\right)}} + \frac{P_s}{1 - e^{-\lambda_{is} t_{lc}\left(\frac{LT_{long}}{LT_{long}+1}\right)}} \quad \textbf{(18)}$$

By substituting equation (18) into equation (17), $E[H_3]$ can be obtained. The UE mean holding time $E[H_5]$ at the external active state of the DRX long cycle S_5 is expressed as follows [15]:

$$E[H_5] = (p_{53}E[N_{lc}^*])t_{ON} \tag{19}$$

The power saving factor $\gamma_{LTE\ DRX\ (3-states)}$ of original LTE DRX (3-states) model can be calculated as the following formula:

$$\gamma_{LTE\ DRX\ (3-states)} = \frac{\pi_2 E[H_2] + \pi_3 E[H_3]}{\sum_{i=1}^{3} \pi_i\, E[H_i]} \tag{20}$$

The power saving factor $\gamma_{LTE\ DRX\ (4-states)}$ of extended LTE DRX (4-states) model can be calculated as the following formula:

$$\gamma_{LTE\ DRX\ (4-states)} = \frac{\pi_2 E[H_2] + \pi_3 E[H_3]}{\sum_{i=1}^{4} \pi_i\, E[H_i]} \tag{21}$$

The Power saving factor $\gamma_{LTE\ DRX\ (5-states)}$ of extended LTE DRX (5-states) model can also be calculated as the following formula:

$$\gamma_{LTE\ DRX\ (5-states)} = \frac{\pi_2 E[H_2] + \pi_3 E[H_3]}{\sum_{i=1}^{5} \pi_i\, E[H_i]} \tag{22}$$

Where π_i belongs to UE steady state probability at state S_i. Due to stationary distribution evaluation, steady state probabilities are estimated by solving balance equation: $\pi_i = \sum_{j=1}^{3,4\ or\ 5} \pi_j\, p_{j,i}$ as i,j are transition states and the node equation: $\sum_{i=1}^{3,4\ or\ 5} \pi_i = 1$. Steady state probabilities of the extended models are calculated as follows [15]:

$$\Pi_{LTE\ DRX\ (4-states)} = \begin{cases} \pi_1 = \dfrac{1 - p_{24}}{1 - p_{24} + p_{12} + p_{12}p_{24} + p_{12}p_{23}} \\ \pi_2 = \dfrac{p_{12}}{1 - p_{24} + p_{12} + p_{12}p_{24} + p_{12}p_{23}} \\ \pi_3 = \dfrac{p_{12}p_{23}}{1 - p_{24} + p_{12} + p_{12}p_{24} + p_{12}p_{23}} \\ \pi_4 = \dfrac{p_{12}p_{24}}{1 - p_{24} + p_{12} + p_{12}p_{24} + p_{12}p_{23}} \end{cases} \tag{23}$$

$$\Pi_{LTE\ DRX\ (5-states)} = \begin{cases} \pi_1 = \dfrac{(1 - p_{35})(1 - p_{24})}{(1 - p_{35})(1 - p_{24}) + p_{12}(1 + p_{24} + p_{23} + p_{23}p_{35} - p_{35} - p_{24}p} \\ \pi_2 = \dfrac{p_{12}(1 - p_{35})}{(1 - p_{35})(1 - p_{24}) + p_{12}(1 + p_{24} + p_{23} + p_{23}p_{35} - p_{35} - p_{24}p} \\ \pi_3 = \dfrac{p_{12}p_{23}}{(1 - p_{35})(1 - p_{24}) + p_{12}(1 + p_{24} + p_{23} + p_{23}p_{35} - p_{35} - p_{24}p} \\ \pi_4 = \dfrac{p_{12}p_{24}(1 - p_{35})}{(1 - p_{35})(1 - p_{24}) + p_{12}(1 + p_{24} + p_{23} + p_{23}p_{35} - p_{35} - p_{24}p} \\ \pi_5 = \dfrac{p_{12}p_{23}p_{35}}{(1 - p_{35})(1 - p_{24}) + p_{12}(1 + p_{24} + p_{23} + p_{23}p_{35} - p_{35} - p_{24}p} \end{cases} \tag{24}$$

Steady state probabilities of the original LTE DRX (3-states) model are given in [16].

2.2.2. HD-DRX Scenario Mathematical Analysis

Figure 5 shows the extended HD-DRX (5-states) system model drawn by using of the Semi-Markov chain model. This extended model is derived from adding only one active state to the DRX short cycle of the original model. Five UE transition states of the extended HD-DRX (5-states) model are defined as the following: active state, light sleep state, beam searching state, deep sleep state and external active state to the DRX short cycle state represented by S_1, S_2, S_3, S_4 and S_5 respectively.

Figure 5 shows the extended HD-DRX (5-states) system model drawn by using of the Semi-Markov chain model. This extended model is derived from adding only one active state to the DRX short cycle of the original model. Five UE transition states of the extended HD-DRX (5-states) model are defined as the following: active state, light sleep state, beam searching state, deep sleep state and external active state to the DRX short cycle state represented by S_1, S_2, S_3, S_4 and S_5 respectively.

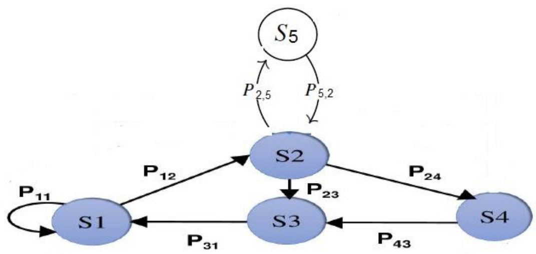


Figure 5. Extended HD-DRX (5-states) Model Based on Semi-Markov Chain

When the UE is indicated with a traffic arrival during the ON duration t_{ON} of the DRX short cycle t_{sc} in the light sleep state S_2, the UE measures the traffic arrival weight compared to the short light traffic threshold value LT_{short}. If the measured weight is greater than LT_{short}, the UE leaves the light sleep state S_2 to the beam searching state S_3 with the transition probability p_{23} as follows:

$$p_{23} = P_{pc}\left(1 - e^{-\lambda_{ipc}t_N}\right)^{LT_{short}+1} + P_s\left(1 - e^{-\lambda_{is}t_N}\right)^{LT_{short}+1} \quad (25)$$

Otherwise, the UE doesn't go to the beam searching state S_3 because it is not necessary to perform beam searching and alignment for traffic lower than LT_{short} as it is dissipated power without many benefits. Therefore, the UE will leave S_2 state to the external active state of DRX short cycle S_5 so that it can be enabled to receive the light data traffic with a transition probability p_{25} as follows:

$$p_{25} = 1 - p_{23} - p_{24} \quad (26)$$

At S_5 state, the UE can't detect any path to leave except the path from S_5 to S_2 with a transition probability p_{52} expressed as follows:

$$p_{52} = 1 \quad (27)$$

When the UE is not indicated with traffic after DRX short cycle timer t_N is expired, the UE leaves from S_2 to the deep sleep state S_4 with a transition probability p_{24} as follows:

$$p_{24} = P_{pc}e^{-\lambda_{ipc}t_N} + P_s e^{-\lambda_{is}t_N} \quad (28)$$

At S_4 state, the UE will be asleep for a longer period compared to S_2 until either the UE wakes up during the ON duration t_{ON} or DRX long cycle t_{lc} is expired. Then, the UE must leave S_4 to S_3 to perform beam searching and alignment as follows:

$$p_{43} = 1 \quad (29)$$

After the beam searching and alignment procedure, the UE leaves the beam searching state S_3 to the active state S_1 as follows:

$$p_{31} = 1 \quad (30)$$

Note that p_{11} and p_{11} are still expressed as in equations (1) and (2), respectively.

The UE mean holding time $E[H_1]$ at sate S_1 is given as follows [12-16]:

$$E[H_1] = \frac{\mu_p - 1}{\lambda_{ip}} + \frac{P_{pc}}{\lambda_{ipc}}\left(1 - e^{-\lambda_{ipc}t_I}\right) + \frac{P_s}{\lambda_{is}}\left(1 - e^{-\lambda_{is}t_I}\right) \quad (31)$$

The UE mean holding time $E[H_2]$ at state S_2 is derived as follows:

$$E[H_2] = (p_{23}E[N_{sc}^{**}] + p_{24}(N_{sc} + LT_{short}) + p_{25}E[N_{sc}^{*}])(tsc - t_{ON}) \quad (32)$$

$E[N_{sc}^{*}]$ is still expressed as in equation (10). $E[N_{sc}^{**}]$ can be also geometrically distributed as follows:

$$E[N_{sc}^{**}] = P_{pc}\left[\frac{1-e^{-\lambda_{ipc}t_N(\frac{LT_{short}+1}{LT_{short}+N_{sc}})}}{1-e^{-\lambda_{ipc}t_{sc}}} - N_{sc}e^{-\lambda_{ipc}t_N(\frac{LT_{short}+1}{LT_{short}+N_{sc}})}\right] + P_s\left[\frac{1-e^{-\lambda_{is}t_N(\frac{LT_{short}+1}{LT_{short}+N_{sc}})}}{1-e^{-\lambda_{is}t_{sc}}} - N_{sc}e^{-\lambda_{is}t_N(\frac{LT_{short}+1}{LT_{short}+N_{sc}})}\right] \quad (33)$$

$E[H_2]$ can be calculated by substitiuting of equations (10) and (33) into equation (32).

The UE mean holding time $E[H_3]$ at the beam searching state S_3 is given as follows [13,14]:

$$E[H_3] = P_{pc}\frac{(1 - e^{-\lambda_{ipc}t_{bs}})}{\lambda_{ipc}} + P_s\frac{(1 - e^{-\lambda_{is}t_{bs}})}{\lambda_{is}} \quad (34)$$

The UE mean holding time $E[H_4]$ at the deep sleep state S_4 is given as follows [12-16]:

$$E[H_4] = E[N_{lc}](t_{lc} - t_{ON}) \tag{35}$$

The UE mean holding time $E[H_5]$ at the external active state of DRX short cycle S_5 can be expressed as follows:

$$E[H_5] = (p_{52}E[N_{sc}^*])t_{ON} \tag{36}$$

Figure 6 shows the extended HD-DRX (6-states) system model by using of the Semi-Markov chain model. This extended model is derived from adding another active state to the DRX long cycle of the original model, in addition to the added one to the DRX short cycle. Six UE transition states of the extended HD-DRX (6-states) model are defined as the following: active state, light sleep state, beam searching state, deep sleep state, external active state to the DRX short cycle state and external active state to the DRX long cycle state represented by S_1, S_2, S_3, S_4 and S_5 respectively.

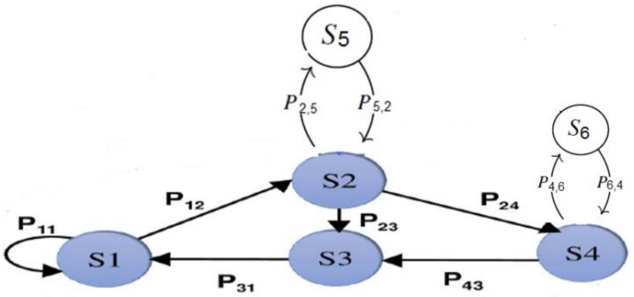


Figure 6. Extended HD-DRX (6-states) Model Based on Semi-Markov Chain

When the UE is indicated with a traffic arrival during the ON duration t_{ON} of the DRX long cycle t_{lc} in the deep sleep state S_4, the UE measures the traffic arrival weight compared to the long light traffic threshold value LT_{long}. If the measured weight is greater than LT_{long}, the UE leaves the deep sleep state S_4 to the beam searching state S_3 with the a transition probability p_{43} as follows:

$$p_{43} = P_{pc}\left(1 - e^{-\lambda_{ipc}t_{lc}}\right)^{LT_{long}+1} + P_s\left(1 - e^{-\lambda_{is}t_{lc}}\right)^{LT_{long}+1} \tag{37}$$

Otherwise, the UE doesn't go to the beam searching state S_3 because it is not necessary to perform beam searching and alignment process for traffic lower than LT_{long} as it is dissipated power without many benefits. Therefore, the UE will leave from S_4 to the external active state to DRX long cycle S_6 with a transition probability p_{46} as follows:

$$p_{46} = 1 - p_{43} \tag{38}$$

At S_6, the UE can't detect any path to leave except from S_6 to S_4 with a transition probability p_{64} expressed as follows:

$$p_{64} = 1 \tag{39}$$

Note that p_{11} and p_{11} are still expressed as in equations (1) and (2), respectively. $E[H_1]$, $E[H_2]$ and $E[H_2]$ are also still expressed as in equations (31), (32) and (34), respectively.

The UE mean holding time $E[H_4]$ at the deep sleep state S_4 must be expressed as follows:

$$E[H_4] = (p_{46}E[N_{lc}^*] + p_{43}E[N_{lc}])(t_{lc} - t_{ON}) \tag{40}$$

The mean value of N_{lc}^* can be expressed as follows:

$$E[N_{lc}^*] = \frac{P_{pc}}{1 - e^{-\lambda_{ipc}t_{lc}\left(\frac{LT_{long}}{LT_{long}+1}\right)}} + \frac{P_s}{1 - e^{-\lambda_{is}t_{lc}\left(\frac{LT_{long}}{LT_{long}+1}\right)}} \tag{41}$$

$E[H_5]$ is still expressed as given by equation (36).

The UE mean holding time $E[H_6]$ at the external active state of DRX long cycle can be expressed as follows:

$$E[H_6] = (p_{64}E[N_{lc}^*])t_{ON} \tag{42}$$

The power saving factor of original HD-DRX (4-states) model can be given by the following formula as follows [13,14]:

$$\gamma_{HD-DRX\,(4-states)} = \frac{\pi_2 E[H_2] + \pi_3 E[H_3]}{\sum_{i=1}^{4} \pi_i\, E[H_i]} \quad (43)$$

The power saving factor of the extended HD-DRX (5-states) model can be derived as follows:

$$\gamma_{HD-DRX\,(5-states)} = \frac{\pi_2 E[H_2] + \pi_3 E[H_3]}{\sum_{i=1}^{5} \pi_i\, E[H_i]} \quad (44)$$

The power saving factor of the extended HD-DRX (6-states) model can be derived as follows:

$$\gamma_{HD-DRX\,(6-states)} = \frac{\pi_2 E[H_2] + \pi_3 E[H_3]}{\sum_{i=1}^{6} \pi_i\, E[H_i]} \quad (45)$$

Similar to LTE DRX scenario mathematical analysis, steady state probabilities are calculated as the following equations:

$$\Pi_{HD-DRX\,(4-states)} = \begin{cases} \pi_1 = \frac{1}{1+p_{12}(1+p_{23}+p_{24}+p_{24}p_{43})} \\ \pi_2 = \frac{p_{12}}{1+p_{12}(1+p_{23}+p_{24}+p_{24}p_{43})} \\ \pi_3 = \frac{p_{12}(p_{23}+p_{24}p_{43})}{1+p_{12}(1+p_{23}+p_{24}+p_{24}p_{43})} \\ \pi_4 = \frac{p_{12}p_{24}}{1+p_{12}(1+p_{23}+p_{24}+p_{24}p_{43})} \end{cases} \quad (46)$$

$$\Pi_{HD-DRX\,(5-states)} = \begin{cases} \pi_1 = \pi_1 p_{11} + \pi_3 p_{31} \\ \pi_2 = \pi_1 p_{12} + \pi_5 p_{52} \\ \pi_3 = \pi_2 p_{23} + \pi_4 p_{43} \\ \pi_4 = \pi_2 p_{24} \\ \pi_5 = \pi_2 p_{25} \end{cases} \quad (47)$$

However the power saving is achieved; the delay cost due to longer sleep durations is existed. The traffic arrival within the active mode comes at the exact time [6,13,14] while the reason for delay is the sleep mode since the UE waits until it wakes up to check if a traffic arrival or not. Time that UE waits is defined as ''Wake-Up delay" [6,13,14]. Not only the both sleep states (light and deep) cause delay but also the beam searching state causes a delay due to the buffered packets at the Base Station. $\boldsymbol{\delta_2}$, $\boldsymbol{\delta_3}$ and $\boldsymbol{\delta_4}$ are average delay due to light sleep, beam searching and deep sleep states respectively. $\boldsymbol{PS_2}$, $\boldsymbol{PS_3}$ and $\boldsymbol{PS_4}$ are a packet call arrival probabilities during light sleep state $\boldsymbol{S_2}$, beam searching state $\boldsymbol{S_3}$ and deep sleep state $\boldsymbol{S_4}$ respectively. The main mathematical equation of the average delay for the original and extended models can be put at the following form [13,14]:

$$E[D] = (\delta_2 \times PS_2) + (\delta_3 \times PS_3) + (\delta_4 \times PS_4) \quad (48)$$

$\boldsymbol{\delta}$ and $\boldsymbol{PS}$ of the original HD-DRX (4-states) model are given in our approach in [14].

For the extended HD-DRX (5-states) and the extended HD-DRX (6-states) models, $\boldsymbol{PS_2}$ and $\boldsymbol{PS_4}$ can be derived as the following formulas:

$\boldsymbol{PS_3}$ is taken from [13,14].

3. Analytical Results and Discussions

In this section, external active states to the original model are analysed through adding one active state to each DRX cycle based on the light traffic threshold value. For adding one active state to the DRX short cycle, extended models are derived as LTE DRX (4-states) and HD-DRX (5-states). For adding another active state to the DRX long cycle, extended models are derived as LTE DRX (5-states) and HD-DRX (6-states). Power saving factor and average delay are the most common measurements estimated to verify the system model success. Moreover, improvement percentages of the extended models compared to the original model are calculated to distinguish which model is better. For LTE DRX scenario, delay may be ignored since beam searching job is not present then power saving factor is only measured. For HD-DRX scenario, delay is a major trade-off since the beam searching state is essential then power saving factor and average delay are both measured. At the end of this paper, a performance comparison is assigned between the LTE DRX and HD-DRX scenarios. European Telecommunications Standards Institute (ETSI) web traffic model parameters are considered [16]. A MATLAB simulation program is a software tool to perform this assignment. Table 1 gives the simulation parameters used in this paper. This section is divided into two sub-sections as follows:

Table 1. Simulation Used Parameters in the Paper

Parameter	Distribution	Mean Value
Inter-Session Idle Time, t_{is}	Exponential	2000 sec
Inter-Session Arrival Rate, λ_{is}	Exponential	1/2000
Inter-Packet Call Idle Time, t_{ipc}	Exponential	30 sec
Inter-Packet Call Arrival Rate, λ_{ipc}	Exponential	1/30
Number of Packet Calls per a Session, N_{pc}	Geometric	μ_{pc} = 5
Number of Packets per a Packet Call, N_p	Geometric	μ_P = 25
Inter-Packet Arrival Time, t_{ip}	Exponential	0.1 sec
Inter-Packet Arrival Rate, λ_{ip}	Exponential	10
DRX Inactivity Timer, t_I	Exponential	2 sec
DRX Short Cycle, t_{sc}	Exponential	2 sec
DRX Long Cycle, t_{lc}	Exponential	10 sec
ON Duration, t_{ON}	Exponential	100 msec
DRX Short Cycle Timer, t_N	Exponential	10 sec
Light Traffic Threshold Values, (LT_{short}, LT_{long})	Random	3,5
Beam Searching Period, t_{bs}	Deterministic	288 msec

3.1. LTE DRX Scenario Analytical Results

In this sub-section, extended LTE DRX (4-states) and extended LTE DRX (5-states) models are evaluated compared to the original LTE DRX (3-states) model due to the power saving factor based on the light traffic threshold value, LT_{short} and LT_{long}.

Figure 7 shows the impact of external active states added to the original LTE DRX (3-states) model on the DRX short cycle power saving factor under different values of the light traffic threshold, LT_{short} and LT_{long}. As the DRX short cycle t_{sc} increases, the power saving factor is exponentially increased. LTE DRX (4-states) model enhances the DRX short cycle power saving factor by about (0.3 – 0.9) % compared to the original LTE DRX (3-states) model. By using ($LT_{short} = 5$), the LTE DRX (4-states) model can achieve better performance than that achieved by using ($LT_{short} = 3$). LTE DRX (5-states) model can also enhance the DRX short cycle power saving factor but with higher performance since it enhances the power saving factor by about 0.3 % compared to the original LTE DRX (3-states) model. Results seem to be linear due to the minor impact of the DRX short cycle on the power saving factor.

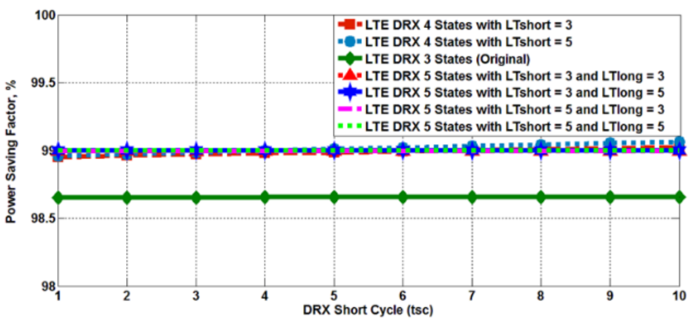


Figure 7. Extended LTE DRX Short Cycle Power Saving Factor

Figure 8 shows the impact of external active states added to the original LTE DRX (3-states) model on the DRX long cycle power saving factor under different values of the light traffic threshold, LT_{short} and LT_{long}. As the DRX long cycle t_{lc} increases, the power saving factor is exponentially increased but with higher results than that done by the DRX short cycle power saving factor since the UE is asleep for a longer duration. LTE DRX (4-states) model enhances the DRX long cycle power saving factor by about 0.3 % compared to the original LTE DRX (3-states) model. By using ($LT_{short} = 5$), the LTE DRX (4-states) model can achieve minor better performance than that achieved by using ($LT_{short} = 3$). LTE DRX (5-states) model enhances the DRX long cycle power saving factor by about 0.8 % compared to the original LTE DRX (3-states) model. The degradation of the power saving factor, at the first slots of DRX long cycle in LTE DRX (5-states) model, is due to the impact of two external active states during UE longer sleep durations. Results seem to be non-linear compared to DRX short cycle results due to the major impact of DRX long cycle on the power saving factor.

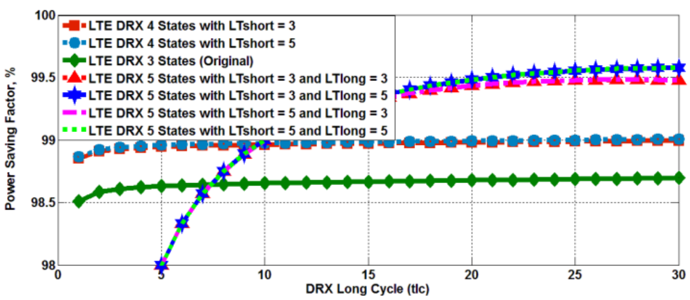


Figure 8. Extended LTE DRX Long Cycle Power Saving Factor

Figure 9 shows the impact of external active states added to the original LTE DRX (3-states) model on the inactivity timer power saving factor under different values of the light traffic threshold, LT_{short} and LT_{long}. As the inactivity timer t_I increases, this means the start of data traffic arrival from the eNodeB and the extension of the listening window by the UE. Therefore, the power saving factor is exponentially decreased. However the inactivity timer power saving factor is reduced, the external active states enhanced it compared to the original LTE DRX (3-states) model. As shown in this figure, the LTE DRX (4-states) model enhances the inactivity timer power saving factor by about (0.3 – 0.9) % compared to the original LTE DRX (3-states) model. By using ($LT_{short} = 5$), the LTE DRX (4-states) model achieves minor better performance than that achieved by using ($LT_{short} = 3$). LTE DRX (5-states) model enhances the inactivity timer power saving factor by about (0.1 – 9) % compared to the original LTE DRX (3-states) model. Due to the minor impact of the inactivity timer on the power saving factor, the results are very convergent because of adding two active states, especially for LTE DRX (5-states) model. It is noticeable that the linearity of the results is related to the same reason.

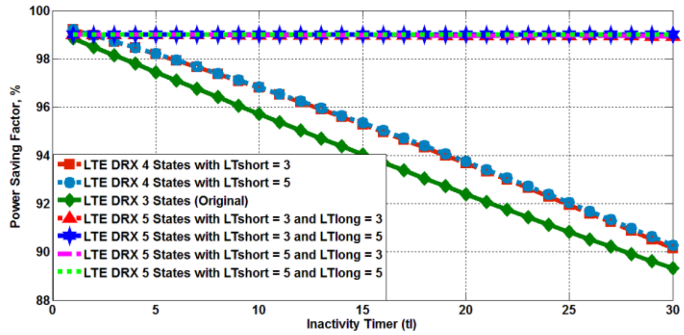


Figure 9. Extended LTE Inactivity Timer Power Saving Factor

Table 2 and Table 3 provide the numerical results of the power saving factor and the improvement percentages, respectively.

Table 2. LTE DRX Power Saving Factor Numerical Results (Original Model and Extended Model)

Model	DRX Short Cycle, t_{sc} (%)	DRX Long Cycle, t_{lc} (%)	Inactivity Timer, t_I (%)	LT_{short}	LT_{long}
LTE DRX (4-states)	98.9489-99.0220	98.8509-98.9942	99.2091-90.1546	3	-
LTE DRX (4-states)	98.9575-99.0620	98.8656-99.0062	99.2186-90.2644	5	-
LTE DRX (5-states)	98.9937-98.9945	90.0000-99.4764	98.9962-98.9286	3	3
LTE DRX (5-states)	98.9994-98.9995	90.0000-99.5765	98.9997-98.9936	3	5
LTE DRX (5-states)	98.9938-98.9949	90.0000-99.4781	98.9963-98.9291	5	3
LTE DRX (5-states)	98.9994-98.9995	90.0000-99.5773	98.9997-98.9936	5	5
Original LTE DRX (3-states)	98.6511-98.6549	98.5076-98.6959	98.8415-89.3312	-	-

Table 3. LTE DRX Power Saving Improvement Percentages

Numerical Results (Original Model Compared to Extended Model)

Model	DRX Short Cycle, t_{sc} (%)	DRX Long Cycle, t_{lc} (%)	Inactivity Timer, t_I (%)	LT_{short}	LT_{long}
LTE DRX (4-states)	0.2978-0.3671	0.2983-0.3433	0.3676-0.8234	3	-
LTE DRX (4-states)	0.3064-0.9651	0.3103-0.3580	0.3771-0.9332	5	-
LTE DRX (5-states)	0.3396-0.3426	Reaches to 0.7805	0.1547-9.5974	3	3
LTE DRX (5-states)	0.3446-0.3483	Reaches to 0.8806	0.1582-9.6624	3	5
LTE DRX (5-states)	0.3400-0.3427	Reaches to 0.7822	0.1548-9.5979	5	3
LTE DRX (5-states)	0.3446-0.3483	Reaches to 0.8814	0.1582-9.6624	5	5
Better Model	LTE DRX (5-states)	LTE DRX (5-states)	LTE DRX (5-states)	5	5

3.2. HD-DRX Scenario Analytical Results

In this sub-section, extended HD-DRX (5-states) and extended HD-DRX (6-states) models are evaluated compared to the original HD-DRX (4-states) model due to both the power saving factor and the average delay based on the light traffic threshold value, $\boldsymbol{LT_{short}}$ *and* $\boldsymbol{LT_{long}}$. This sub-section is divided into two other sub-sections as follows:

3.2.1. Power Saving Factor

Figure 10 shows the impact of external active states added to the original HD-DRX (4-states) model on the DRX cycle parameters power saving factor under different values of the light traffic threshold, LT_{short} and LT_{long} in dB representation. Table 4 provides the power saving factor numerical results for the original HD-DRX (4-states), extended HD-DRX (5-states) and extended HD-DRX (6-states) models.

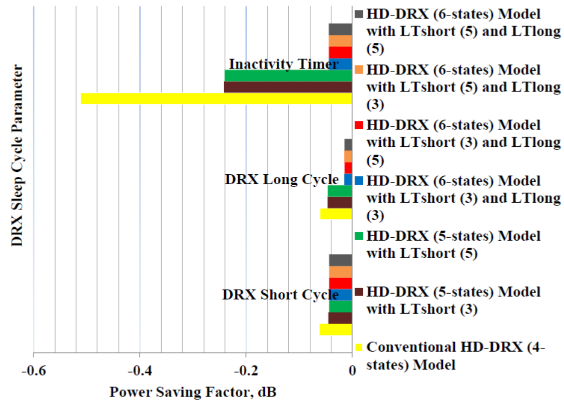


Figure 10. DRX Cycle Parameters Power Saving Factor for Original and Extended HD-DRX Models

Table 4. HD-DRX Power Saving Factor Numerical Results (Original Model and Extended Models

Model	DRX Short Cycle, t_{sc} (%)	DRX Long Cycle, t_{lc} (%)	Inactivity Timer, t_I (%)	LT_{short}	LT_{long}
HD-DRX (5-states)	98.8837-98.9610	98.7795-98.9315	99.1233-94.5809	3	-
HD-DRX (5-states)	98.8873-98.9983	98.7879-98.9380	99.1296-94.6162	5	-
HD-DRX (6-states)	98.9998-99.0001	90.0480-99.6535	99.0009-98.9816	3	3
HD-DRX (6-states)	99.0005-99.0008	90.0479-99.6610	99.0018-98.9803	3	5
HD-DRX (6-states)	98.9998-99.0002	90.0468-99.6535	99.0008-98.9815	5	3
HD-DRX (6-states)	99.0005-99.0010	90.0466-99.6609	99.0016-98.9802	5	5
Original HD-DRX (4-states)	98.5679-98.5720	98.4157-98.6155	98.7948-88.8934	5	5

Figure 11 shows the power saving factor improvement percentages for the extended HD-DRX (5-states) and HD-DRX (6-states) models compared to the original HD-DRX (4-states) model in dB representation. Table 5 clarifies these improvement percentages of each extended model compared to the original one.

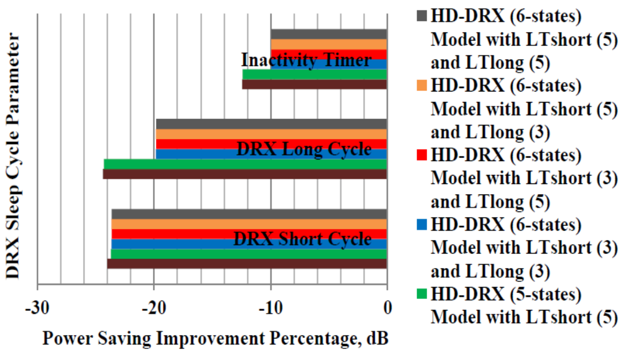


Figure 11 DRX Cycle Parameters Power Saving Improvement Percentages of Extended Models Compared to Original Model

Table 5. HD-DRX Power Saving Improvement Percentages Numerical Results (Original Model Compared to Extended Model)

Model	DRX Short Cycle, t_{sc} (%)	DRX Long Cycle, t_{lc} (%)	Inactivity Timer, t_I (%)	LT_{short}	LT_{long}
HD-DRX (5-states)	0.3158-0.3890	0.3160-0.3638	0.3285-5.6875	3	-
HD-DRX (5-states)	0.3194-0.4263	0.3225-0.3722	0.3348-5.7228	5	-
HD-DRX (6-states)	0.4281-0.4319	Reaches to 1.0380	0.2061-10.0882	3	3
HD-DRX (6-states)	0.4288-0.4326	Reaches to 1.0455	0.2070-10.0869	3	5
HD-DRX (6-states)	0.4282-0.4319	Reaches to 1.0380	0.2060-10.0881	5	3
HD-DRX (6-states)	0.4290-0.4326	Reaches to 1.0454	0.2068-10.0868	5	5
Better Model	HD-DRX (6-states)	HD-DRX (6-states)	HD-DRX (6-states)	5	5

3.2.2. Average Delay

Table 6 provides the average delay numerical results of the original HD-DRX (4-states), extended HD-DRX (5-states), extended HD-DRX (6-states) models. This table can also indicate which model is better for delay.

Table 6. HD-DRX Average Delay Numerical Results (Original Model and Extended Model)

Model	DRX Short Cycle, t_{sc} (sec)	DRX Long Cycle, t_{lc} (sec)	Inactivity Timer, t_I (sec)	LT_{short}	LT_{long}
HD-DRX (5-states)	0.8593-0.9145	0.0138-6.4614	0.8851-0.4773	3	-
HD-DRX (5-states)	0.8594-0.8900	0.0136-6.4612	0.8849-0.4773	5	-
HD-DRX (6-states)	0.2232-0.2784	0.0090-1.0044	0.2326-0.1352	3	3
HD-DRX (6-states)	0.1059-0.1611	0.0080-0.4008	0.1124-0.0707	3	5
HD-DRX (6-states)	0.2233-0.2540	0.0088-1.0043	0.2325-0.1352	5	3
HD-DRX (6-states)	0.1060-0.1366	0.0079-0.4006	0.1122-0.0707	5	5
Original HD-DRX (4-states)	0.8600-1.1061	0.0177-6.4652	0.8891-0.4789	-	-
Status	Increasing	Increasing	Decreasing	-	-
Better Model	HD-DRX (6-states)	HD-DRX (6-states)	HD-DRX (6-states)	5	5

3.3. Performance Comparison

In this sub-section, the paper evaluates the performance of external active states to the original model via LTE DRX and HD-DRX comparison. To achieve high fair comparison, the power saving factor is the best metric since the both are power saving scenarios. The performance comparison is carried out under similar cases and the same DRX timing values. Table 7 observes the performance comparison numerical results to differentiate between LTE DRX and HD-DRX power saving scenarios.

Table 7. LTE DRX and HD-DRX Scenarios Performance Comparison Numerical Results (Extended Models)

Model	DRX Short Cycle, t_{sc} (%)	DRX Long Cycle, t_{lc} (%)	Inactivity Timer, t_I (%)	External Active State	Better Model
LTE DRX (4-states)	98.9489-99.0620	98.8509-99.0062	99.2091-90.2644	One	√
HD-DRX (5-states)	98.8837-98.9983	98.7795-98.9380	99.1233-94.6162		
LTE DRX (5-states)	98.9937-98.9995	90-99.5773	98.9997-98.9286	Two	
HD-DRX (6-states)	98.9998-99.0010	90.0466-99.6610	99.0018-98.9802		√

As shown in the above table, it is clear that when another active state is added to the DRX long cycle, in addition to added one to the DRX short cycle, this enhances the performance as in extended LTE DRX (5-states) and extended HD-DRX (6-states) models compared to extended LTE DRX (4-states) and extended HD-DRX (5-states) models, respectively. The extended HD-DRX (6-states) model is the best one to save power in spite of the UE beam searching process. This proves that the external active states to the original model save power consumption by the HD-DRX scenario more than that saved by the LTE DRX scenario. Thus, extended HD-DRX models are preferred rather than extended LTE DRX models.

4. Conclusion

In this paper, two scenarios are introduced for the Discontinuous Reception (DRX) sleep mode in the Fourth Generation Long Term Evolution (4G LTE) networks and the Fifth Generation New Radio (5G NR) networks. These scenarios are defined as LTE DRX and Hybrid Directional-DRX (HD-DRX). The paper presents the idea of external active states to each DRX cycle of the original LTE DRX (3-states) and HD-DRX (4-states) models. By adding only one active state to the DRX short cycle, the extended LTE DRX (4-states) and HD-DRX (5-states) models are produced. By adding another active state to the DRX long cycle, in addition to the added one to the DRX short cycle, the extended LTE DRX (5-states) and HD-DRX (6-states) models are produced. The User Equipment (UE) transition states during the extended models are determined based on the light traffic threshold value by using a Semi-Markov chain model for LTE DRX and HD-DRX scenarios. In LTE DRX scenario, the power saving factor is enhanced by the extended LTE DRX (4-states) and LTE DRX (5-states) models by about (0.1 – 9) % compared to that of the original LTE DRX (3-states) model. In HD-DRX scenario, the power saving factor is enhanced by the extended HD-DRX (5-states) and HD-DRX (6-states) models by about (0.2 – 10) % compared to that of the original HD-DRX (4-states) model. Due to the beam searching process, the average delay by the extended HD-DRX (5-states) and HD-DRX (6-states) models is reduced by about (8 – 6000) msec compared to that of the original HD-DRX (4-states) model. After a performance comparison is assigned between the LTE DRX and HD-DRX scenarios, extended HD-DRX models are preferred rather than extended LTE DRX models.

Acknowledgements

Mustafa M. Sallam and Mohammed Hassna M. Mahmoud thank Giza Higher Institute for Engineering and Technology (GEI) in Giza, Egypt for its financial and practical support to construct this paper. Great thank to our colleagues and team work in GEI.

References

1. Mrtin-Oerez, J., Cominardi, L., Bernardos, C. J., de la Oliva, A., & Azcorra, A. (2019). Modeling mobile edge computing deployments for low latency multimedia services. *IEEE Transactions on Broadcasting*, *65*(2), 464-474.
2. Cao, T., Xu, C., Wang, M., Jiang, Z., Chen, X., Zhong, L., & Grieco, L. A. (2019). Stochastic optimization for green multimedia services in dense 5G networks. *ACM Transactions on Multimedia Computing, Communications, and Applications* (*TOMM*), *15*(3), 1-22.
3. Padmanabhan, N., Ahmed, M., & Ahmed, M., & Bhattacharya, K. (2019). Battery energy storage systems in energy and reserve markets. *IEEE Transactions on Power Systems*, *35*(1), 215-226.
4. Mushtaq, M. S., Fowler, S., & Mellouk, A. (2017, May). Power saving model for mobile device and virtual base station in the 5G era. In *2017 IEEE International Conference on Communications* (*ICC*) (pp. 1-6). IEEE.
5. Nafea, H. B., Sallam, M. M., & Zaki, F. W. (2021). Study of DRX sleep mode performance on virtual base station energy saving in 5g networks. *Wireless Personal Communications*, *118*(4), 3251-3270.
6. Zhao, T., Wu, J., Zhou, S., & Niu, Z. (2014, November). Energy-delay tradeoffs of virtual base stations with a computational-resource-aware energy consumption model. In *2014 IEEE International Conference on Communication Systems* (pp. 26-30). IEEE.
7. Koc, A. T. Jha, S. C., Vannithamby, R., & Torlak, M. (2014). Device power saving and latency optimization in LTE-A networks through DRX configuration. *IEEE Transactions on Wireless Communications*, *13*(5), 2614-2625.
8. Ramazanali, H., & Vinel, A. (2015). Performance evaluation of LTE/LTE-a DRX: A Markovian approach. *IEEE Internet of Things Journal*, *3*(3), 386-397.
9. Balasubramanya, N. M., Lampe, L., Vos, G., & Bennett, S. (2016). DRX with quick sleeping: A novel mechanism for energy-efficient IoT using LTE/LTE-A. *IEEE Internet of Things Journal*, *3*(3), 398-407.
10. Tseng, C. C., Wang, H. C., Kuo, F. C., Ting, K. C., Chen, H. H., & Chen, G. Y. (2015). Delay and power consumption in LTE/LTE-A DRX mechanism with mixed short and long cycles. *IEEE Transactions on Vehicular Technology*, *65*(3), 1721-1734.
11. Maheshwari, M. K., Agiwal, M., Saxena, N., & Roy, A. (2018). Directional discontinuous reception (DDRX) for mmWave enabled 5G communications. *IEEE*

Transactions on Mobile Computing, *18*(10), 2330-2343.
12. Zhou, L., Xu, H., Tian, H., Gao, Y., Du, L., & Chen, L. (2008, September). Performance analysis of power saving mechanism with adjustable DRX cycles in 3GPP LTE. In *2008 IEEE 68th Vehicular Technology Conference* (pp. 1-5). IEEE.
13. Maheshwari, M. K., Agiwal, M., Saxena, N., & Roy, A. (2017). Hybrid directional discontinuous reception (HD-DRX) for 5G communication. *IEEE Communications Letters*, 21(6), 1421-1424.
14. Sallam, M. M., Nafea, H. B. & Zaki, F. W. (2018). Comparative study of power saving and delay in LTE DRX, directional-DRX and hybrid-directional DRX. *Wireless Personal Communications*, *98*(4), 3299-3317.
15. Fowler, S., Shahidullah, A. O., Osman, M., Karlsson, J. M., &Yuan, D. (2015). Analytical evaluation of extended DRX with additional active cycles for light traffic. *Computer Networks*, *77*, 90-102.
16. Nafea, H. B., Sallam, M. M., & Zaki, F. W. (2018). Performance evaluation of sleep mode on power saving in WiMAX IEEE 802.16m and LTE DRX. *Wireless Personal Communications*, *102*(1), 183-200.