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Performance Evaluation of LTE/LTE-A DRX: A Markovian Approach

Hawar Ramazanali and Alexey Vinel

***Abstract*—LTE/LTE-A are emerging communication technologies on the way towards 5G telecommunication systems. Ubiquitous adoption of connectivity in between different kinds of sensors, wearable devices and other low-power equipment raises an importance of the energy-efficient wireless communications. In LTE/LTE-A the Discontinuous Reception Mechanism (DRX) aims at power saving of User Equipment (UE) devices. In the paper we present an analysis of DRX, which is novel in two dimensions. First, our analytical approach is different to existing ones due to the use of Markov chain instead of the semi-Markov ones. Secondly, along with the generic traffic models we also analyze the efficiency of DRX for military training application systems, what has not been done before. We suggest few practical recommendations regarding the DRX parameters tuning also.**

***Index Terms*—LTE/LTE-A, DRX, power saving, energy efficiency, wake-up delay, machine-to-machine communication, military training, IoT.**

I. INTRODUCTION

Emerging concept of the Internet of Things (IoT) assumes the ubiquitous machine-to-machine (M2M) communications, what shall result in new applications and services. Road vehicles, industrial automation, healthcare systems are the few examples of areas where M2M connectivity is foreseen to have an impressive potential. Military training systems, though being discussed in the literature less often, yet introduce another example of IoT paradigm.

The radio networks in military training systems are objects of emerging requirements for multimedia streaming and lower latencies for data transmission. These radio networks have until recently been proprietary systems aimed at Non-Line-of-Sight (NLOS) and very low data rates. Due to the new requirements, commercial systems have been evaluated and LTE/LTE-A has also been put in use. However in order to provide realistic training there is a need for long operating time for the mobile nodes, User Equipments (UEs), in the training network. To check the ability of meeting this demand, the advanced DRX mechanism is investigated in the paper. We aim at maximizing the power saving factor to increase UEs' operating time in a military training applications with different types of traffic.

In this paper we present Markov models for the LTE/LTE-A DRX mechanism for both uplink and downlink traffic. The results are verified by simulations. We show the impact of the DRX parameters on the power saving factor and on the mean wake-up delay for the UE. Particularly we present results for a simple traffic model representing military traffic and a traffic model for multimedia using simplified bounded-Pareto distribution. Our results show that the DRX mechanism is crucial for power saving in LTE/LTE-A devices by discontinuous reception, also it can be designed to meet a traffic deadline and provides flexibility to adjust the mechanism through its parameters to achieve power saving for bursty traffic.

One of the earlier research works performed on the DRX mechanism was [1] where a 4 state semi-Markov model was presented and verified against simulation experiments, for the universal mobile telecommunications system (UMTS) power saving mechanism using traffic with exponentially distributed inter-packet times. Following on this work a number of papers, amongst them [2]-[8] has been published with similar approaches using at least 3 state semi-Markov models with different types of traffic models. Out of these [4] uses the lowest resolution of the DRX mechanism representation for its model states, and this is down to the level of ON duration and sleep cycles. There are also other works that either do not represent all DRX model states in their model states [9], present only analytic expressions for performance metrics without a Markov chain model [10], use simulation only [11], or are pure measurement based research work [12]. Out of the papers presenting analytical models we have in Table I presented the model type and traffic model used for respective work. Our work is the only LTE/LTE-A DRX mechanism using Markov chain approach with a model state for every DRX sub frame (SF), enabling the lowest resolution analysis which gives a larger flexibility for analyzing the behavior of the system. This could for example be used to calculate the contribution to the delay from the respective states, *ON* and *sleep*, in which the traffic was originally generated. Other methods for power efficiency in wireless communication systems are power efficient designs [13] or power allocation/control [14]-[15].

The main contributions of this work are the following:

- a novel Markov chain model of the LTE/LTE-A DRX mechanism with long and short DRX cycles, which is different to previously reported semi-Markovian models;
- an analysis of the power saving maximization, whilst still meeting a wake-up delay requirement;
- performance evaluation of the DRX mechanism for military training scenarios including multimedia.

The remaining paper is structured as follows. In Section II, the DRX mechanism is presented. In Section III, the model for the complete DRX mechanism is presented. In Section IV, the "reduced" model for the DRX mechanism without short cycles is presented accompanied by propositions on how to

H. Ramazanali is with SAAB Training and Simulation, Husqvarna, Sweden. E-mail: hawar.ramazanali@saabgroup.com (corresponding author);

A. Vinel is with Halmstad University, Halmstad Sweden. E-mail: alexey.vinel@hh.se

meet a wake-up delay and maximize the power saving factor. In section V the results are presented and discussed in two subsections for different kinds of traffic. Section VI concludes the paper.

II. POWER SAVING IN LTE/LTE-A

A. LTE/LTE-A DRX Mechanism

An LTE device can be either in RRC_Idle or RRC_Connected mode [16]. DRX mechanism can be used in both modes [17] but is in this work described only for RRC_Connected mode. The data transmission which is of interest is handled in this mode only, while the RRC_Idle handles control signaling and there is no data transmission (since a RRC connection has not been established). The DRX mechanism is an optional feature in the LTE network to save power in the UEs [17]. It allows the UE to transit from a continuous reception mode where the radio module is turned on and monitoring the Physical Downlink Control Channel (PDCCH) (*active mode*) to a discontinuous reception mode (*DRX cycle*) where the radio module is turned on and monitoring the PDCCH only during a fraction of the time to save power once an inactivity timer has expired. The DRX cycle consists of an ON duration where the UE radio module is turned on and monitors the PDCCH for indication of scheduled transmissions and a sleep mode where the radio module is turned off to save power. If traffic is indicated during the ON duration then the UE will wake up to active state after the completed DRX cycle and the inactivity timer will be started.

During the active period, the inactivity timer will be restarted whenever there is any transmission or reception, or scheduled traffic is indicated in the PDCCH. The DRX mechanism consists also of two types of DRX cycles, short and long. The short DRX cycle is optional and once enabled it will be cycled until expiry of the Short DRX timer, expressed in number of consecutive short DRX cycles, whilst there is no traffic. After the expiry of Short DRX cycle timer the long DRX cycle is started and it is cycled until traffic is indicated in ON and UE wakes up. Traffic will be indicated only in the ON duration which means that when traffic intended for the UE is generated in the base station during UE sleep cycle, it will be indicated in the next ON duration and the UE wakes up after the following completed DRX cycle.

The operation of DRX is summarized in Fig. 1 with the following notations: N_1 is an *onDurationTimer* in short DRX cycle, N_2+N_1 is a *shortDRX-Cycle*, N_3 is an *onDurationTimer* in long DRX cycle, N_4+N_3 is a *longDRX-Cycle*, N_5 is a *drx-InactivityTimer* and N_s is a *drxShortCycleTimer* for maximum number of short DRX cycles. The ON duration have the same length for both short and long DRX cycle. All parameters, beside N_s, are expressed in number of SFs with the duration of 1 ms which is the shortest scheduling interval for LTE downlink and uplink.

B. Simplifications in DRX Mechanism Operation

For simplicity and clarity when describing the DRX mechanism and the results, our DRX model is deviating from the standard [16]-[17] on the following points:

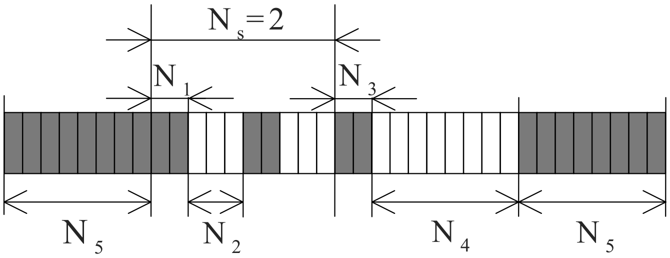

Fig. 1: Illustration of the DRX operation

- PDCCH is monitored in the same SF as when the Inactivity timer is restarted, i.e. the first SF in the inactivity period, instead of the next SF according to the standard. This change is done to simplify the operation and the modelling since it is expected to have a minor impact on the performance.
- DRX cycle is started immediately after the Inactivity timer expiry instead of on the *drxStartOffset* SF that in the standard [17] specifies where the DRX cycle starts. This simplification is made since this parameter is not necessary for the performance evaluation and has not been considered in previous work with analytical models. However if it would have been used the UE would have been kept in *active* state for a longer time until it is allowed to start DRX cycle at the specified SF.
- When either uplink or downlink traffic is detected during the *ON* duration, the UE transitions to *active* state after the completed DRX cycle, i.e. both ON and sleep cycle. The standard [17] states that if the PDCCH indicates a new transmission (downlink or uplink) then *drx-InactivityTimer* shall be started or restarted. But no further details are stated explicitly explaining the procedure. This assumption is made to maintain the DRX mechanism structure as well as applying the same procedure to both downlink and uplink data. The advantages are a clear understanding of the mechanism procedures and using only one model for both traffic directions. The influence of the results may be longer delays but we present the worst case delay for both traffic directions and the DRX mechanism.
- For each DRX cycle a separate timer is used for *ON* duration, N_1 or N_3, and the sleep cycle, N_2 or N_4, see Fig. 1. In the standard a timer is used for the whole DRX cycle, either *shortDRX-Cycle* or *longDRX-Cycle*, with the addition of a timer for *ON* duration. There is however no impact on the results since this difference is just in how the timers are applied.
- Three states are distinguished, *ON*, *sleep* and *active*, while the standard assumed that *ON* is part of the *active* state. This assumption do not have any impact on the results.

C. Traffic Model

It is assumed that traffic is generated/arriving with a probability p in each sub frame as long as no traffic has arrived yet in DRX state. For the uplink (UL) the traffic is generated in the UE and for the downlink (DL) this traffic is generated in the base station. However is it assumed that both generated uplink and downlink traffic affects the DRX mechanism in the same way, i.e. both UL and DL generates the same wake up procedure. The traffic direction is still used in this work for distinction of traffic models based on the traffic direction. When there is any traffic schedule for the UE this is indicated in the PDCCH. The PDCCH is monitored by the UE during ON and active state.

Summarizing the traffic model is as follows:

- A probability that traffic arrives during the SF is denoted as p. Arrivals of traffic in different SFs are statistically independent.
- If traffic arrives during an active period then it is transmitted immediately. If traffic arrives during a non-active period then it is placed in the queue.
- Only the arrival of the first traffic during DRX is modeled and placed in the buffer until the device wakes-up.
- Each UE is able to update the content of traffic in its buffer by the newly arrived one.

The resulting modeled LIFO queue with size one is a valid assumption for military training systems and IoT where the newest data is of interest.

In addition to the above described traffic model, a simple model representing military training traffic is used. Also a traffic model for multimedia traffic based on simplified bounded-Pareto distribution is presented and evaluated by a simulator with a queue registering all generated traffic (also during DRX). These additional traffic models are presented in Section V.

D. Performance metrics

Our performance metrics are the *mean wake-up delay* and the *power saving factor*. The latter is defined as the fraction of time the UE device is in the sleep mode.

The wake-up delay is defined as the time from the traffic is generated to when the device wakes up (enters *active* state). The maximum wake-up delay for UE occurs when traffic is generated in the first SF in the sleep cycle and sums up to a complete sleep cycle and a complete DRX cycle. This assumption is made both for downlink and uplink to obtain a unified worst case delay, even if uplink could be detected during any state and hence shorter wake-up delay could have been assumed.

III. LTE/LTE-A DRX "COMPLETE" MARKOVIAN MODEL

A. Preliminaries

A Markov chain has been developed to model the complete DRX mechanism including short and long DRX cycles as well as an active mode. The model is started at zero SF and initiated in the active period. Once inactivity timer has expired the short DRX cycle is entered, and if no traffic arrived waking the UE up and N_s short DRX cycles has been cycled then next DRX cycle will be of a long DRX type. The long DRX cycle will be cycled as long as there is no traffic coming.

The model is Markovian with discrete time and a state transition every SF. The time spent in the state is thereby geometrically distributed.

TABLE I: Related work models

Reference	**Traffic**	**Model**
[1]	ETSI traffic model	Semi-Markov
[2]	ETSI and background	Semi-Markov
[3]	Simplified bounded-Pareto	Semi-Markov
[4]	Poisson	Semi-Markov
[5]	Poisson	Semi-Markov
[6]	Poisson	Semi-Markov
[7]	ETSI traffic model	Semi-Markov
[8]	ETSI traffic model	Semi-Markov
[9]	Poisson	Semi-Markov

The advantage of our proposed complete model is that not only can stationary probabilities for the short and long DRX and active states be obtained but also the probability of each individual SF which gives a larger flexibility for analyzing the behavior of the system. State probabilities for groups of SFs can be calculated as well for different analysis purposes. Buffer status, i.e. if the buffer is empty or not for a specific SF, is also available in the states enabling further delay analysis.

B. Markov Chain: States

The following notation $\left\{ \substack{Q, a, b \\ i, j} \right\}$ is used to describe the DRX states of the Markovian model where $Q \in \{ON, Sleep, Active\}$ is the DRX mechanism states, $a \in \{short, long\}$ annotates the DRX cycle type, and $b \in \{no, yes, yes*\}$ indicates if there is traffic in the buffer where *yes* indicates that the traffic in the buffer was generated during ON duration which will wake up the UE after the completed DRX cycle and *yes** indicates that the traffic was generated only during the sleep cycle which will wake-up the UE after the next completed DRX cycle. Notation i is the current SF index or likewise the current timer value given in number of SFs, within the specified DRX state and j gives the current value of the *drxShortCycleTimer*, given in maximum number of consecutive short DRX cycles also denoted as N_s. With this notation for the model states every sub frame in every DRX state can be addressed and expressed in clarity.

Following the presented notation convention our Markov chain comprises of the states as presented in Table II.

C. Markov Chain: Transition Probabilities

The transition probability between states can be any of the following:

- p probability that traffic arrives, as long as there is no traffic in the UE buffer;
- $1-p$ probability that traffic do not arrive, as long as there is no traffic in the UE buffer;
- 1 there is a traffic in the UE buffer.

The Markov chain is presented in Fig. 2. The notations in the figure is different from the description in III-B by using this representation $\{Q_{i,j}\ a,\ b\}$ and the following abbreviations: ON (O), Sleep (S), Active (A), short (s), long (l).

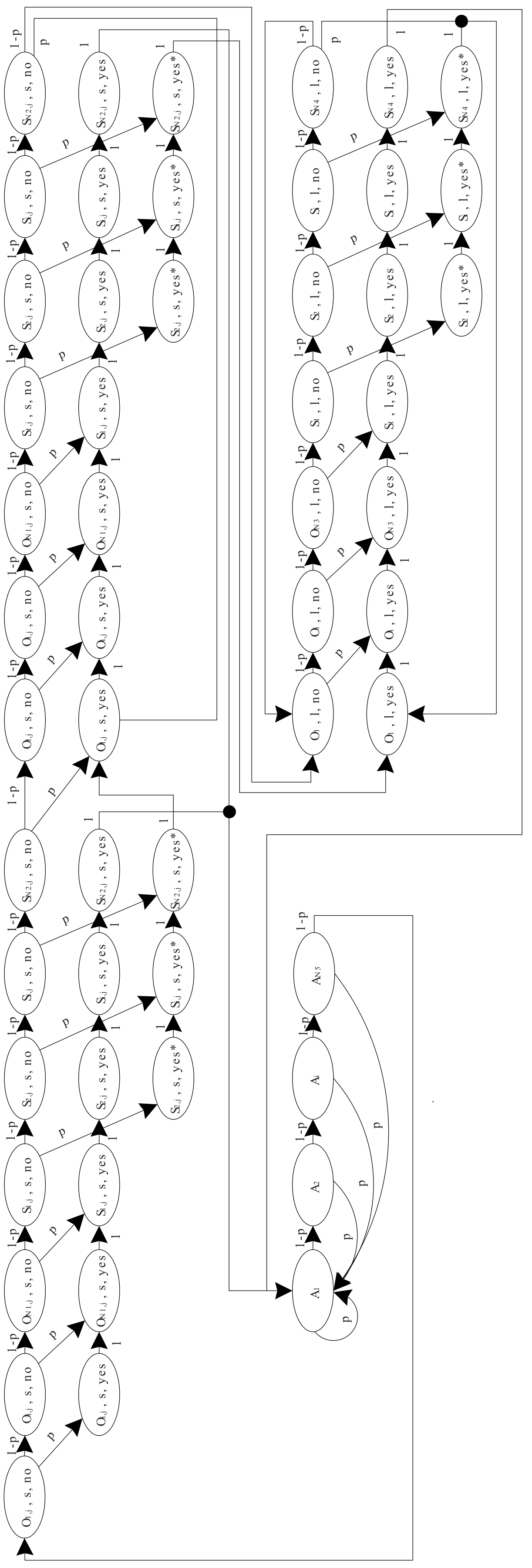

Fig. 2: Complete model with enabled short DRX cycle

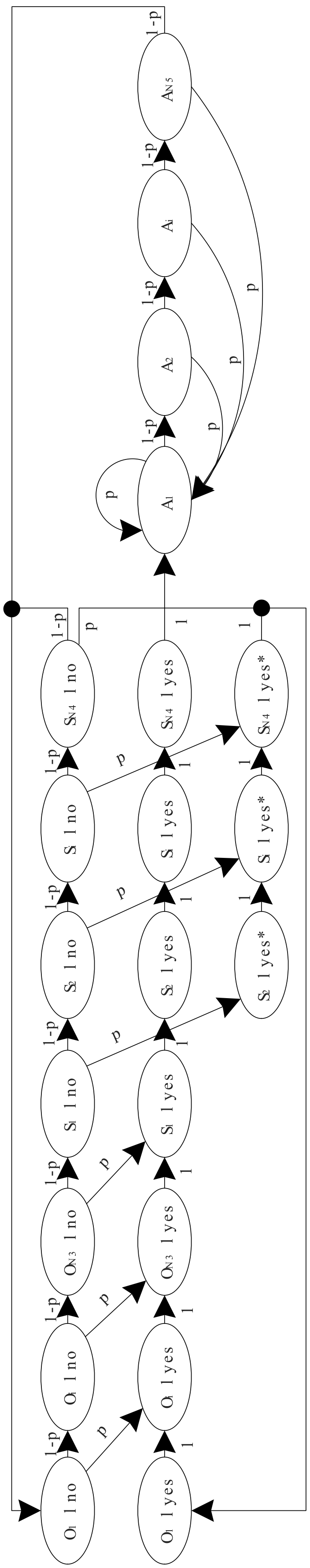

Fig. 3: Reduced model with disabled short DRX cycle

TABLE II: Markov Chain: States

N	Notation	UE State / Wake up moment	*i,j* ranges $[number\,of\,SFs]$
1	$\left\{ {ON,short,no \atop i,j} \right\}$	UE in the *i*-th SF of the *j*-th short DRX sleep cycle. There is no traffic in the UE buffer.	$1 \leq i \leq N_1$, N_1 (*onDurationTimer*) $1 \leq j \leq N_s$, N_s (*drxShortCycleTimer*)
1a	$\left\{ {ON,long,no \atop i} \right\}$	UE in the *i*-th SF of the long DRX sleep cycle. There is no traffic in the UE buffer.	$1 \leq i \leq N_3$, N_3 (*onDurationTimer*)
2	$\left\{ {ON,short,yes \atop i,j} \right\}$	UE in the *i*-th SF of the *j*-th short DRX sleep cycle. There is traffic in the UE buffer, wake up after completed DRX cycle	$1 \leq i \leq N_1$, N_1 (*onDurationTimer*) $2 \leq j \leq N_s$, N_s (*drxShortCycleTimer*)
2a	$\left\{ {ON,long,yes \atop i} \right\}$	UE in the *i*-th SF of the long DRX sleep cycle. There is traffic in the UE buffer, wake up after completed DRX cycle	$1 \leq i \leq N_1$, N_1 (*onDurationTimer*)
3	$\left\{ {Sleep,short,no \atop i,j} \right\}$	UE in the *i*-th SF of the *j*-th short DRX sleep cycle. There is no traffic in the UE buffer.	$1 \leq i \leq N_2$, N_2 (*shortDRX-Cycle - onDurationTimer*) $1 \leq j \leq N_s$, N_s (*drxShortCycleTimer*)
3a	$\left\{ {Sleep,long,no \atop i} \right\}$	UE in the *i*-th SF of the long DRX sleep cycle. There is no traffic in the UE buffer.	$1 \leq i \leq N_4$, N_4 (*longDRX-Cycle - onDurationTimer*)
4	$\left\{ {Sleep,short,yes \atop i,j} \right\}$	UE in the *i*-th SF of the *j*-th short DRX sleep cycle. There is traffic in the UE buffer, wake up after completed DRX cycle	$1 \leq i \leq N_2$, N_2 (*shortDRX-Cycle - onDurationTimer*) $1 \leq j \leq N_s$, N_s (*drxShortCycleTimer*)
4a	$\left\{ {Sleep,long,yes \atop i} \right\}$	UE in the *i*-th SF of the long DRX sleep cycle. There is traffic in the UE buffer, wake up after completed DRX cycle.	$1 \leq i \leq N_4$, N_4 (*longDRX-Cycle - onDurationTimer*)
5	$\left\{ {Sleep,short,yes* \atop i,j} \right\}$	UE in the *i*-th SF of the *j*-th short DRX sleep cycle. Traffic in the UE buffer was generated during sleep. UE will wake up after next completed DRX cycle	$2 \leq i \leq N_2$, N_2 (*shortDRX-Cycle - onDurationTimer*) $1 \leq j \leq N_s$, N_s (*drxShortCycleTimer*)
5a	$\left\{ {Sleep,long,yes* \atop i} \right\}$	UE in the *i*-th SF of the long DRX sleep cycle. Traffic in the UE buffer was generated during sleep. UE will wake up after next completed DRX cycle	$2 \leq i \leq N_4$, N_4 (*longDRX-Cycle - onDurationTimer*)
6	$\left\{ {Active \atop i} \right\}$	UE in the *i*-th SF of the active state. Zero wake-up delay	$1 \leq i \leq N_5$, N_5 (*drx-InactivityTimer*)

D. Markov Chain: Stationary Distribution

Since all states for the Markov chain are aperiodic, recurrent and nonnull, they are all ergodic and the Markov chain is then ergodic. The system then has equilibrium state probabilities. The notation used for the stationary probabilities of the model states is $Pr\left\{ {Q, a, b \atop i, j} \right\}$ where the model notations follow the same convention as previously.

Our strategy is to express all the stationary probabilities from the state probability of $Pr\left\{ {ON, short, no \atop 1, 1} \right\}$ expressed in (1) with its sub functions (2),(3) and (4). The stationary probabilities for: ON duration for short DRX cycle (5), short DRX sleep cycle (6), ON duration for long DRX cycle (7), long DRX sleep cycle (8) and active state (9) are then expressed with (1). Expression (1) as well as the pattern of the stationary state probabilities (5)-(9) has been extracted from the normalization equation.

$$Pr\left\{ {ON, short, no \atop 1,1} \right\} = \frac{1}{A+B+C} \tag{1}$$

$$A = (N_1+N_2) \cdot \left(1 + \frac{1}{(1-p)^{N_1+N_2}-1}\right) \cdot \\ \cdot \left((1-p)^{N_s(N_1+N_2)}(1-p)^{-N_2} - (1-p)^{N_1}\right) \tag{2}$$

$$B = (N_3+N_4) \cdot (1-p)^{N_s(N_1+N_2)} \cdot \\ \cdot \left(\frac{(1-p)^{N_3}}{1-(1-p)^{N_3+N_4}} + (1-p)^{-N_2}\right) \tag{3}$$

$$C = \left(\frac{\left(1-(1-p)^{N_s(N_1+N_2)}\right)}{(1-p)^{N_5}} + \right. \\ \left. + \frac{\frac{(1-p)^{N_s(N_1+N_2)}}{1-(1-p)^{N_3+N_4}} \cdot \left(1-(1-p)^{N_s(N_3+N_4)}\right)}{(1-p)^{N_5}}\right) \cdot \frac{1-(1-p)^{N_2}}{p} \tag{4}$$

$$Pr\left\{ON\,in\,short\,DRX\,cycle\right\} = \left\{ {ON, short, no \atop 1,1} \right\} \cdot \\ \cdot \left(N_1 + \frac{N_1}{(1-p)^{N_1+N_2}-1} \cdot (1-p)^{\frac{N_s(N_1+N_2)}{N_2}} - (1-p)^{N_1}\right) \tag{5}$$

$$Pr\left\{Sleep\,in\,short\,DRX\,cycle\right\} = \left\{ {ON, short, no \atop 1,1} \right\} \cdot \\ \cdot \left(N_2 + \frac{N_2}{(1-p)^{N_1+N_2}-1} \cdot (1-p)^{\frac{N_s(N_1+N_2)}{N_2}} - (1-p)^{N_1}\right) \tag{6}$$

$$Pr\left\{ON\,in\,long\,DRX\,cycle\right\} = \left\{ {ON, short, no \atop 1,1} \right\} \cdot \\ \cdot N_3\,(1-p)^{N_s(N_1+N_2)} \cdot \left(\frac{(1-p)^{N_3}}{1-(1-p)^{N_3+N_4}} + (1-p)^{-N_2}\right) \tag{7}$$

$$Pr\left\{Sleep\,in\,long\,DRX\,cycle\right\} = \left\{ {ON, short, no \atop 1,1} \right\} \cdot \\ \cdot N_4 \cdot (1-p)^{N_s(N_1+N_2)} \cdot \left(\frac{(1-p)^{N_3}}{1-(1-p)^{N_3+N_4}} + (1-p)^{-N_2}\right) \tag{8}$$

$$\begin{aligned} Pr\left\{Active\right\} = 1 - (Pr\left\{ON\,in\,short\,DRX\,cycle\right\} + \\ + Pr\left\{ON\,in\,long\,DRX\,cycle\right\} + \\ + Pr\left\{Sleep\,in\,short\,DRX\,cycle\right\} + \\ + Pr\left\{Sleep\,in\,long\,DRX\,cycle\right\}) \end{aligned} \tag{9}$$

E. Performance metrics

The mean wake-up delay is obtained from Little's law that expresses the average time spent waiting in the queue as a ratio between the average number of customers in the queue and the average arrival rate. As explained previously the system is assumed to have a LIFO queue with size one and only the delay for the first arrived traffic is obtained. Let X (10) be the stationary probability that there is traffic in the buffer. It consists of two components: X_s for short DRX cycle and X_l for long DRX cycle each expressing the probability that there is traffic in the buffer:

$$X = X_s + X_l \tag{10}$$

$$\begin{aligned} & X_s = \begin{Bmatrix} ON, short, no \\ 1,1 \end{Bmatrix} \cdot \\ & \cdot \Bigg(\Bigg(\frac{(1-p)^{N_s(N_1+N_2)} - (1-p)^{N_1+N_2}}{(1-p)^{N_1+N_2} - 1} \Bigg) \cdot \\ & \cdot \Bigg((N_1+N_2)(1-p)^{-N_2} - 1 + \frac{(1-p)^{N_1} - (1-p)}{p} - \\ & - N_2 (1-p)^{N_1} \Bigg) + (1-p)^{N_1} \Bigg(\frac{(1-p)^{N_s(N_1+N_2)} - 1}{(1-p)^{N_1+N_2} - 1} \Bigg) \cdot \\ & \cdot \Bigg(N_2 + \frac{(1-p)^{N_2} - 1}{p} \Bigg) + N_1 + N_2 - 1 + \\ & + \frac{(1-p)^{N_1} - (1-p)}{p} - N_2 (1-p)^{N_1} \Bigg) \end{aligned} \tag{11}$$

$$\begin{aligned} & X_l = \begin{Bmatrix} ON, short, no \\ 1,1 \end{Bmatrix} \cdot \Bigg(\frac{(1-p)^{N_s(N_1+N_2)}}{1 - (1-p)^{N_3+N_4}} \Bigg) \cdot \\ & \cdot \Bigg(N_3 + N_4 - 1 - (1-p)^{N_3} + (N_3+N_4)(1-p)^{N_3} - \\ & - (N_3+N_4)(1-p)^{N_3+N_4} + \frac{(1-p)^{N_3} - (1-p)}{p} + \\ & + (1-p)^{N_3} \frac{(1-p)^{N_4} - (1-p)}{p} \Bigg) + \\ & + \begin{Bmatrix} ON, short, no \\ 1,1 \end{Bmatrix} \Bigg((1-p)^{(N_s-1)(N_1+N_2)} \Big((1-p)^{N_1} - \\ & - (1-p)^{N_1+N_2} (N_3+N_4) \Bigg) \end{aligned} \tag{12}$$

Finally, Little's law is written as follows. The mean wake-up delay is defined as the probability that there is traffic in the buffer divided by the probability that traffic will be generated into the buffer:

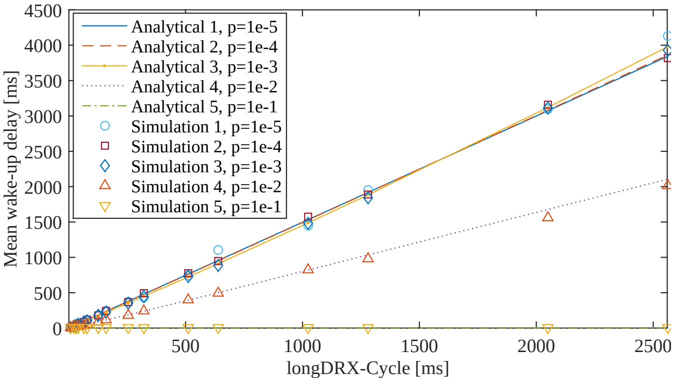

Fig. 4: Verification of complete model – Mean wake-up delay

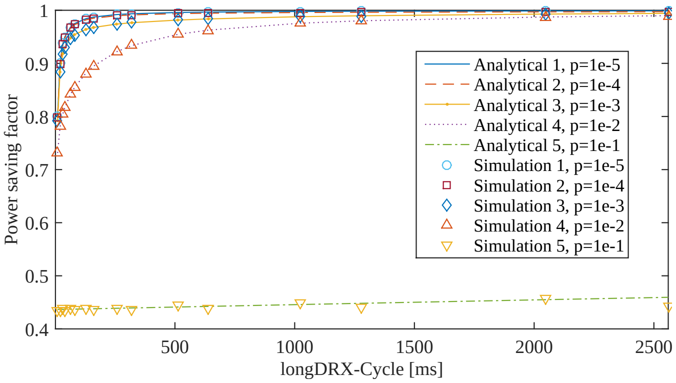

Fig. 5: Verification of complete model – Power saving factor

$$E\left[d\right] = \frac{X}{p\left(1-X\right)} \tag{13}$$

The power saving factor η is obtained according to (14) and is defined as the portion of time the UE spends time in sleep state, both short and long DRX sleep cycle.

$$\begin{aligned} \eta = Pr\left\{Sleep\,in\,short\,DRX\,cycle\right\} + \\ + Pr\left\{Sleep\,in\,long\,DRX\,cycle\right\} \end{aligned} \tag{14}$$

F. Validation

The model is verified by using traffic with different interarrival times $t = \{100e3, 10e3, 1e3, 1e2, 1e1\}$ in ms converted to $p = \frac{1}{t}$. The analytical model is verified against the simulator for this interval of traffic for both mean wake-up delay Fig. 4 and power saving factor Fig. 5. The values of the used DRX parameter set are $N_1 = N_3 = 2, N_2 = 10$, $N_5 = 10$ and $N_s = 8$.

IV. LTE/LTE-A DRX "REDUCED" MARKOVIAN MODEL WITH DISABLED SHORT DRX CYCLE

A. Propositions

The model presented in this section is referred to as a reduced one since the short DRX cycle is disabled. The disabling of the short DRX cycle and the consideration of this model is motivated by propositions below.

Proposition 1: Let the short and long DRX cycles both be enabled and d_{max} be a deadline for a wake-up delay. Then the deadline is always met if $2N_4 + N_3 < d_{max}$, where N_3 is the ON duration and N_4 is the long DRX sleep cycle.

Proof: This proposition directly follows from the operation of the DRX. In the worst delay case traffic is generated with deadline d_{max} in the first SF of the long sleep cycle. The worst case delay is then $N_4 + N_3 + N_4$ and the deadline will then always be met if $N_4 + N_3 + N_4 < d_{max}$. ■

Proposition 2: Let the short DRX cycles be disabled and d_{max} be a deadline for a wake-up delay. Then the deadline is always met if $2N_4 + N_3 < d_{max}$, where N_3 is the ON duration and N_4 is the long DRX sleep cycle.

Proof: The proof is analogous to the proof of proposition 1. ■

Therefore, enabling/disabling of the short DRX cycle does not influence the conditions for meeting the wake-up deadline.

Proposition 3: Let the short DRX cycles be disabled and the inactivity timer N_5 be set to its minimum value, then the power saving factor is maximized.

Proof: Since the same ON state duration is used for both short and long DRX cycles, the percentage of time in the sleep state, is larger for a long DRX cycle compared to a short cycle while $N_4 > N_2$. It is also necessary to keep the inactivity timer value as low as possible, to further avoid consuming power by staying in active state when there is no scheduled traffic. ■

B. Markov Chain

By disabling the short DRX cycle the reduced model is obtained, Fig. 3. The notation from section III is generic and valid also here. The states for the reduced model are described in Table III. The reduced Markov chain is presented in Fig. 3 and follows the same logic as the complete one. The approach for obtaining the stationary probabilities is also the same. From the normalization equation the expression for $\left\{\begin{matrix} ON, long, no \\ 1 \end{matrix}\right\}$ (15) is obtained and the stationary probabilities for the states are obtained for *ON* duration (16), *sleep* state (17) and *active* state (18).

$$Pr\left\{\begin{matrix} ON, long, no \\ 1 \end{matrix}\right\} = \frac{1}{A_0 + B_0 + C_0} \tag{15}$$

$$A_0 = N_3 + N_3 \cdot \left((1-p)^{N_3} - (1-p)^{N_3+N_4} \right)$$

$$B_0 = N_4 + N_4 \cdot \left((1-p)^{N_3} - (1-p)^{N_3+N_4} \right)$$

$$C_0 = \frac{\left(1 - (1-p)^{N_3+N_4}\right) \cdot \left(1 - (1-p)^{N_5}\right)}{p\,(1-p)^{N_5}}$$

$$Pr\left\{ON\,in\,long\,DRX\,cycle\right\} = \left\{\begin{matrix} ON, long, no \\ 1 \end{matrix}\right\} \cdot \tag{16}$$
$$\cdot \left(N_3 + N_3 \cdot \left((1-p)^{N_3} - (1-p)^{N_3+N_4} \right) \right)$$

$$Pr\left\{Sleep\,in\,long\,DRX\,cycle\right\} = \left\{\begin{matrix} ON, long, no \\ 1 \end{matrix}\right\} \cdot \tag{17}$$
$$\cdot \left(N_4 + N_4 \cdot \left((1-p)^{N_3} - (1-p)^{N_3+N_4} \right) \right)$$

$$Pr\left\{Active\right\} = 1 - \left(Pr\left\{ON\,in\,long\,DRX\,cycle\right\} + \tag{18}$$
$$+ Pr\left\{Sleep\,in\,long\,DRX\,cycle\right\}\right)$$

C. Performance metrics

The same as in complete model, the mean wake-up delay is computed by Little's law. Let X_0 be the sum of all probabilities where traffic has arrived i.e. when $b \in \{Yes, Yes*\}$:

$$E\left[d_0\right] = \frac{X_0}{p\,(1 - X_0)} \tag{19}$$

where

$$X_0 = Pr\left\{\begin{matrix} ON, long, no \\ 1 \end{matrix}\right\} \cdot \frac{1}{p} \cdot \tag{20}$$
$$\cdot \Big(p^2 \left(N_1 + N_2\right) (1-p)^{N_1+N_2-1} -$$
$$-p\,(1-p)^{N_1} \left(N_1 + N_2\right) (1-p)^{N_2-1} +$$
$$+ \left((1-p)^{N_2} + \left(N_1 + N_2\right) p \right) (1-p)^{N_1} - 1 + \left(N_1 + N_2\right) p \Big).$$

The power saving factor is defined as the portion of time the UE spends in sleep and it is simply:

$$\eta_0 = Pr\left\{Sleep\,in\,long\,DRX\,cycle\right\} \tag{21}$$

D. Validation

The reduced model is verified, in the same way as the complete model, for both mean wake-up delay Fig. 6 and power saving factor Fig. 7. The values of the used DRX parameter set are $N_3 = 2$ and $N_5 = 10$.

V. Performance Evaluation

A. Preliminaries

The results for the DRX mechanism evaluation are divided into two subsections presenting firstly military training traffic results and secondly multimedia traffic results. In subsection V-B propositions 2 and 3 have been used for meeting the wake-up deadlines while maximizing power saving factor by using the reduced DRX mechanism. Results are presented using a simple traffic model representing military training application. In subsection V-C results are presented for the complete DRX mechanism using a simulator enabled to queue all traffic during DRX cycle together with a multimedia traffic model with simplified bounded-Pareto distribution. Since the traffic arrival model used here does not have memoryless properties, the simulators are used for this evaluation instead.

The valid DRX parameter values from the 3GPP standard [16]-[17] are used. A short and fixed ON duration parameter is assumed and it is not further investigated due to it being

TABLE III: Markov Chain: States for model with disabled short DRX cycle

N	Notation	UE State / Wake up moment	i ranges $[number\ of\ SFs]$
1	$\left\{ \substack{ON,long,no \\ i} \right\}$	UE in the i-th SF of the long DRX sleep cycle. There is no traffic in the UE buffer.	$1 \leq i \leq N_3$, N_3 (*onDurationTimer*)
2	$\left\{ \substack{ON,long,yes \\ i} \right\}$	UE in the i-th SF of the long DRX sleep cycle. There is traffic in the UE buffer, wake up after completed DRX cycle	$1 \leq i \leq N_3$, N_3 (*onDurationTimer*)
3	$\left\{ \substack{Sleep,long,no \\ i} \right\}$	UE in the i-th SF of the long DRX sleep cycle. There is no traffic in the UE buffer.	$1 \leq i \leq N_4$, N_4 (*longDRX-Cycle - onDurationTimer*)
4	$\left\{ \substack{Sleep,long,yes \\ i} \right\}$	UE in the i-th SF of the long DRX sleep cycle. There is traffic in the UE buffer, wake up after completed DRX cycle.	$1 \leq i \leq N_4$, N_4 (*longDRX-Cycle - onDurationTimer*)
5	$\left\{ \substack{Sleep,long,yes* \\ i} \right\}$	UE in the i-th SF of the long DRX sleep cycle. Traffic in the UE buffer was generated during sleep. UE will wake up after next completed DRX cycle	$2 \leq i \leq N_4$, N_4 (*longDRX-Cycle - onDurationTimer*)
6	$\left\{ \substack{Active \\ i} \right\}$	UE in the i-th SF of the active state. Zero wake-up delay	$1 \leq i \leq N_5$, N_5 (*drx-InactivityTimer*)

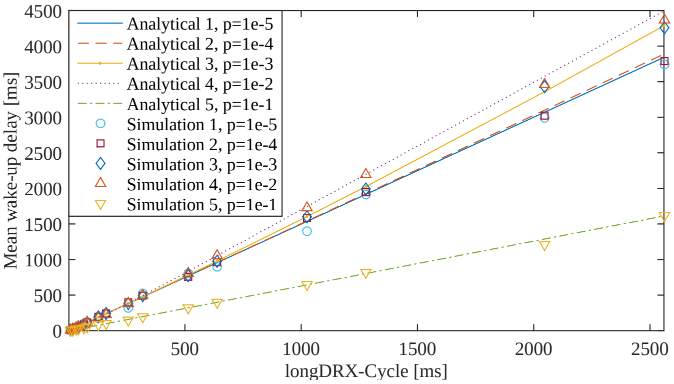

Fig. 6: Verification of reduced model – Mean wake-up delay

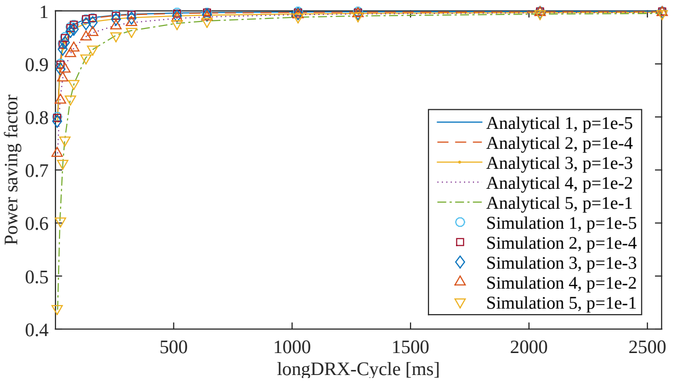

Fig. 7: Verification of reduced model – Power saving factor

TABLE IV: DRX Parameters

Name	Notation	Range [SFs]
onDurationTimer	$N_1 = N_3$	1, 2, 3, 4, 5 6, 8, 10, 20, 30, 40 50, 60, 80, 100, 200
shortDRX-Cycle	$N_1 + N_2$	2, 5, 8, 10, 16, 20 32, 40, 64, 80, 128, 160 256, 320, 525, 640
longDRX-Cycle	$N_3 + N_4$	10, 20, 32, 40, 64, 80 128, 160, 256, 320, 512 640, 1024, 1280, 2048 2560
drx-InactivityTimer	N_5	1, 2, 3, 4, 5, 6, 8, 10, 20 30, 40, 50, 60, 80, 100 200, 300, 500, 750 1280, 1920, 2560
drxShortCycleTimer	N_s	1,...,16

a parameter primarily used for providing the scheduler flexibility, even if it certainly influences both power saving and delay. The valid range and the values for the DRX parameters are according to Table IV.

B. Military training traffic results

In this case the impact of the DRX mechanism on the delay and the power saving factor is investigated for a military training application. Military training traffic can be compared to IoT traffic with long latencies and large mean interarrival times, in the order of seconds. The mobile nodes (UEs) in a military training network consist of mostly two kinds of player types; soldiers and vehicles. Their traffic pattern and requirements specifically within a LTE network has been characterized for a realistic military training application scenario and resulted in the traffic model in Table V. For each player type there may be several types of traffic for each direction, uplink or downlink. Each traffic type is expressed with a uniformly distributed mean interarrival time that represents the average behavior of a specific traffic type and a maximum latency. For each player type all traffic in each direction is merged into a new mean interarrival time $\bar{t}$ which is used together with the lowest latency requirement.

This results in the 4 stages of traffic as in Table V with the combination of uplink or downlink traffic for soldiers and vehicles. It should be noted as already has been described that the division of uplink and downlink traffic is for presentation of military traffic purpose since it is assumed that both the uplink and downlink traffic are detected with the same procedure, i.e. during the ON duration only. Meaning that wake-up delay is calculated in the same way for both traffic directions.

Mean interarrival time $\bar{t}$, is expressed in number of SFs or ms, then $p = \frac{1}{\bar{t}}$.

TABLE V: Military application traffic model

	Soldier	**Vehicle**
Uplink	Latency= 3s $\bar{t} = \frac{10e3+100e3}{2} = 55e3$ $p = \frac{1}{55e3}$	Latency=0.5s $\bar{t} = \frac{5e3+30e3}{2} = 17.5e3$ $p = \frac{1}{17.5e3}$
Downlink	Latency=1-3s $\bar{t} = \frac{250+30e3}{2} = 15.125e3$ $p = \frac{1}{5.125e3}$	Latency=1-3s $\bar{t} = \frac{250+60e3}{2} = 30.125e3$ $p = \frac{1}{30.125e3}$

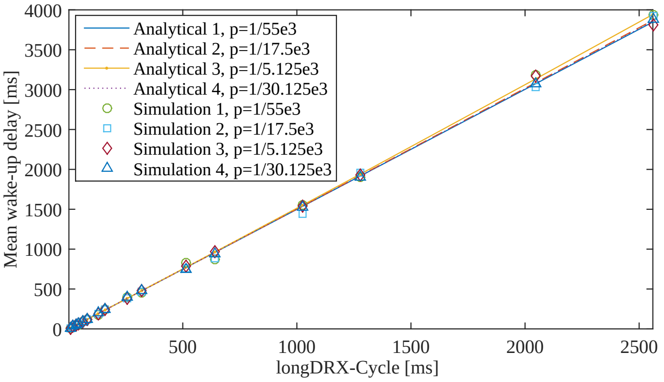

Fig. 8: Military traffic model – Mean wake-up delay

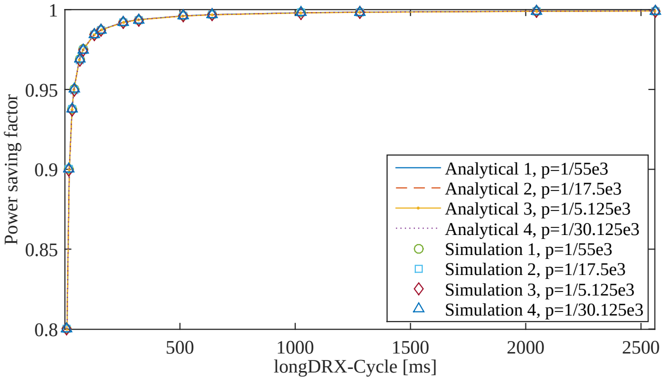

Fig. 9: Military traffic model – Power saving factor

The results for the military traffic model can be seen in Fig. 8 and 9 for mean wake-up delay and power saving factor respectively. Since the results are almost indistinguishable for the player types and the traffic directions, it is assumed the current difference in mean interarrival times do not affect the wake-up delay of the power saving factor in a noticeable way. The four different cases then just need to meet their respective wake-up deadlines for fulfilling the traffic latency requirements according to proposition 2. This gives that the *longDRX-Cycle* shall be $N_4 < \frac{(d_{max}-N_3)}{2}$ and selected from the valid range of values from Table IV. The $N_3 = 2ms$, parameter is fixed and the $N_5 = 1$ parameter is selected based on proposition 3 to maximize the power saving factor.

Vehicle player type with uplink traffic needs to meet a wake-up deadline $d_{max} = 500$ ms so the *longDRX-Cycle* shall be $N_4 < \frac{(d_{max}-N_3)}{2} = 249$ ms, this gives a valid value of 160 ms. The maximum power saving factor will then be 0.9875 for this player type using current parameter values.

Both vehicle and soldier with downlink traffic need to meet a deadline of $d_{max} = 1$ s so the *longDRX-Cycle* shall be $N_4 < \frac{(d_{max}-N_3)}{2} = 499$ ms, this gives a valid value of 320 ms. The maximum power saving factor will then be 0.9937 for these player types using current parameter values.

Soldier with uplink traffic needs to meet a deadline of 3s *longDRX-Cycle* shall be $N_4 < \frac{(d_{max}-N_3)}{2} = 1499$ ms, this gives a valid value of 1280 ms. The maximum power saving factor will then be 0.9984 for this player type using current parameter values.

C. *Multimedia results*

In this subsection the complete DRX mechanism as described in section III is used together with a traffic model generating interarrival times modeling multimedia traffic for evaluation of the DRX mechanism behavior.

1) Traffic model: In [3] it is described that multimedia traffic exhibits self-similarity properties and that the Pareto distribution fits well into the packet interarrival time of self-similar traffic. In the 3GPP traffic model [18] the bounded-Pareto distribution is used and it provides a lower L and also an upper H limit for the distribution, that in our model represents the traffic interarrival times. Additionally to avoid complicated mathemathical derivations, a simplified bounded-Pareto distribution is used in the 3GPP traffic model and also in [3] that we adopt. By using inverse transform sampling the formula for generating truncated Pareto distribution is obtained. Given a random number U with a uniform distribution on the interval $\left(\left(\frac{L}{H}\right)^{\alpha}, 1\right]$ the formula for generating random numbers of simplified bounded-Pareto distribution is:

$$x = \frac{L}{U^{1/\alpha}} \tag{22}$$

where $1.1 \leq \alpha \leq 1.9$ for self-similair traffic.

Two cases are investigated in detail for evaluating the effect of the DRX mechanism on the wake-up delay and the power saving factor when self-similar traffic is used. In case one only the delay caused by the DRX cycle is investigated without considering the active state. In case two the active part is also considered and hence the impact of the inactivity timer/active state on the delay. For both cases it is assumed that traffic can arrive and will be registered at any SF during the DRX cycle, unlike the models in section III and IV that only registers the first arrived traffic during the DRX cycle. This means that a queue is used that during DRX cycle registers all the generated traffic and is emptied upon entering *active* state whereby the (DRX created) wake-up delay is obtained for all the traffic that was generated since previous *active* state.

2) Case 1 - Do not consider active state: In this case it is assumed that traffic can arrive and will be registered in any SF in the UE or in the base station during DRX. However only the delay incurred by the DRX cycle is considered for the mean wake-up delay and not the contribution of the active state, i.e. traffic generated during active state with zero wake up delay do not contribute to the mean wake-up delay for the UE.

If multimedia traffic according to the traffic model above is generated in a UE, it can be assumed that there will not be a big difference of the pattern of the traffic if the military traffic model in Table V is added onto the multimedia traffic. Assuming that the multimedia traffic is a uplink stream for supervision purpose, we then use a deadline of 500 ms for this traffic. The shortest wake-up deadline that needs to be met is then d_{max} = $500ms$ and proposition 1 gives us that N_4 < $\frac{(d_{max}-N_3)}{2}$ = 249 when N_3 = $2ms$. From the range of DRX parameter values in Table IV it is obtained that N_4 = $160ms$ is the largest long DRX cycle value fulfilling this requirement.

The *onDurationTimer* and the *drxShortCycleTimer* parameters will affect the results but they are not crucial for designing the DRX functionality which leaves us with 3 parameters to evaluate. The evaluation is performed in three stages with one DRX parameter at each stage. The most important parameter is selected first which is the long sleep cycle since it is critical to meet a wake-up delay. Out of the remaining two parameters the *drxInactivityTimer* is selected as second since it can affect the result drastically, for example for certain type of traffic if the *drxInactivityTimer* is large enough then the UE can spend a large portion of the time in active mode and drastically decrease both delay and possible power saving factor. The *shortDRX-Cycle* is selected as the third parameter since it is not critical for meeting the traffic deadline as long as N_3 ≤ N_4 as is indirectly given since *largeDRX-Cycle* shall be a multiple of *shortDRX-Cycle* according to the standard [16]-[17], also selecting *drxShortCycleTimer* within any of its valid range is not immediately foreseen to cause a drastic change in terms of the impact of the *shortDRX-Cycle* parameter. For each stage both the evaluations are done based on the defined performance metrics.

If nothing else is stated then the following parameter values are used; N_1 = N_3 = $2ms$, N_2 = $10ms$, N_4 = $160ms$, N_5 = $1ms$ and N_s = 8. The Pareto parameter α is evaluated in the range of self-similair traffic in every stage.

Stage 1: It is clear from Fig. 10 and 11 that increasing *longDRX-Cycle* increases the power saving factor with increased mean wake-up delay as a result. The pattern is similair for all α values.

Stage 2: It can not be determined that the *drxInactivityTimer* can affect the mean-wake up delay if its contribution is not considered in the delay, so mean wake-up delay is not analyzed further here. Evaluating the *drxInactivityTimer* (Fig. 12) it is clear that when this timer value is increased the UE is spending more time in active state than in DRX cycle and the power saving factor is decreased to zero for higher values of *drxInactivityTimer* in precence of the traffic.

Stage 3: Having evaluated the drastic effect of *drxInactivityTimer* on the power saving factor without considering its effect on the mean wake-up delay, we show that under current parameter set, the maximum difference in power saving factor is not more than ≈ 9 – 33% within the valid ranges of *shortDRX-Cycle* values (Fig. 14). The mean wake-up delay is at the lowest in the middle of the valid range of *shortDRX-Cycle* values (Fig. 13). It can be seen that very short values creates the longest mean wake-up delays values since it puts the UE into long sleep faster.

3) Case 2 - Consider active state: Similar to case 1 there is no queuing restriction during DRX however the *active* state contribution to mean wake-up delay is considered here, i.e. traffic generated during *active* state have zero wake-up delay and will contribute to the mean wake-up delay.

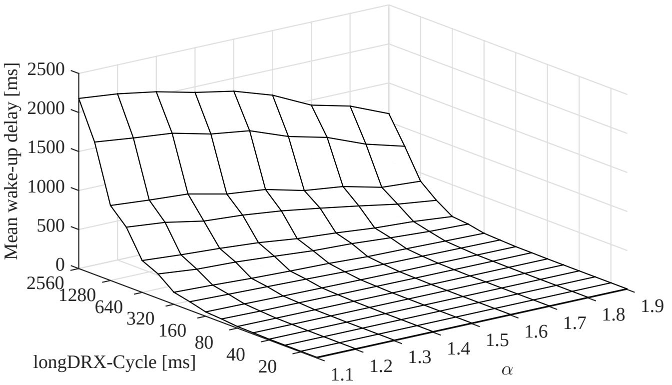

Fig. 10: Case 1, Stage 1 – Mean wake-up delay

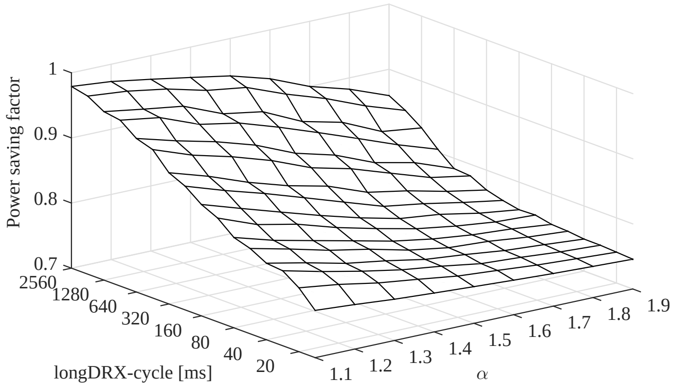

Fig. 11: Case 1, Stage 1 – Power saving factor

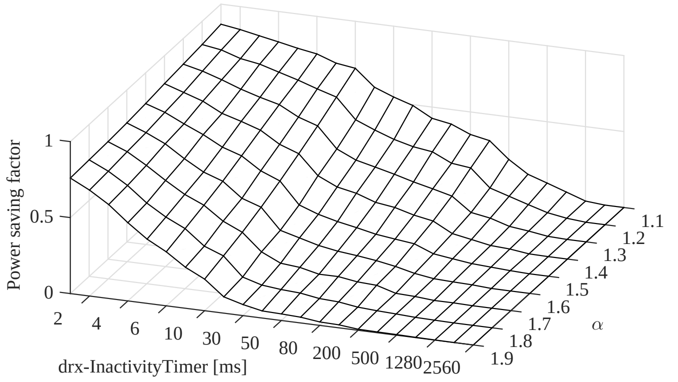

Fig. 12: Case 1, Stage 2 – Power saving factor

Stage 1: The impact of the *longDRX-Cycle* on the performance metrics when considering the *active* state (Fig. 15-16) are not distinguishable compared to when *active* state is not considered (Fig. 10-11). The trend is the same, longer *longDRX-Cycle* increases delay and power saving factor.

Stage 2: The expected result of the increase of the *drxInactivityTimer* upon the mean wake-up delay is verified by Fig. 17 where the mean wake-up delay is zero after sufficiently long timer value. Comparing the impact of *drxInactivityTimer* on the power saving delay, no clear difference is distinguishable between case 1 (Fig. 12) and case 2 (Fig. 18).

Stage 3: The difference between the impact of *shortDRX-*

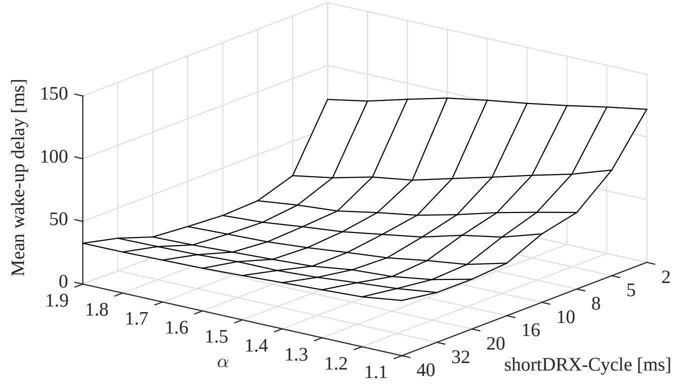

Fig. 13: Case 1, Stage 3 – Mean wake-up delay

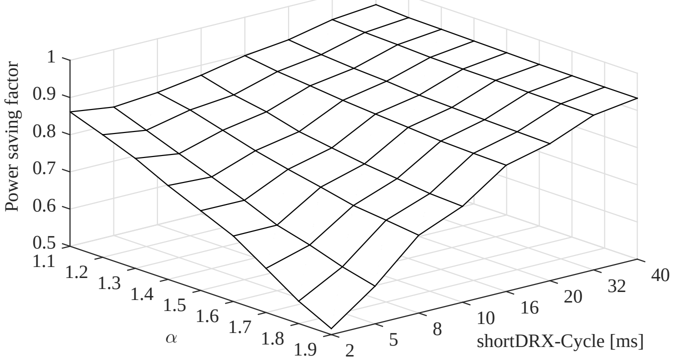

Fig. 14: Case 1, Stage 3 – Power saving factor

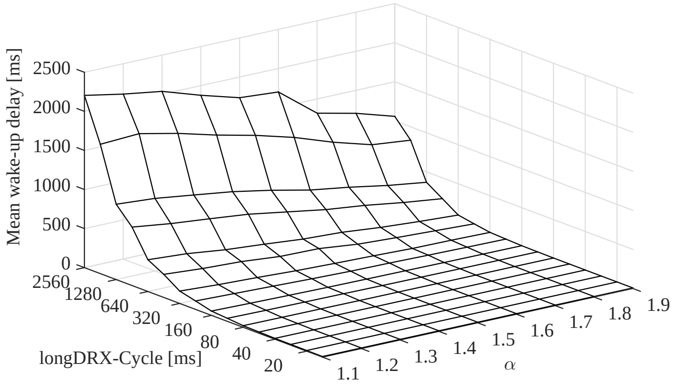

Fig. 15: Case 2, Stage 1 – Mean wake-up delay

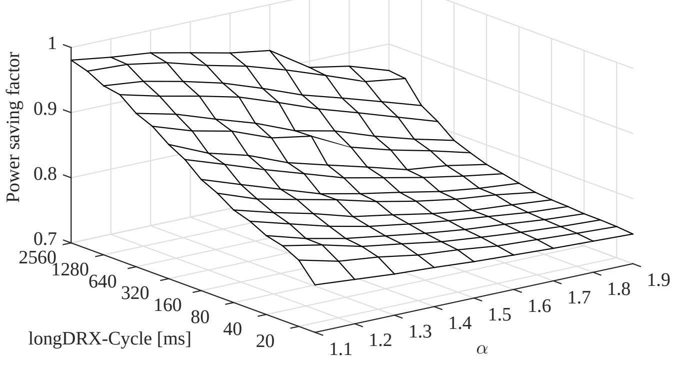

Fig. 16: Case 2, Stage 1 – Power saving factor

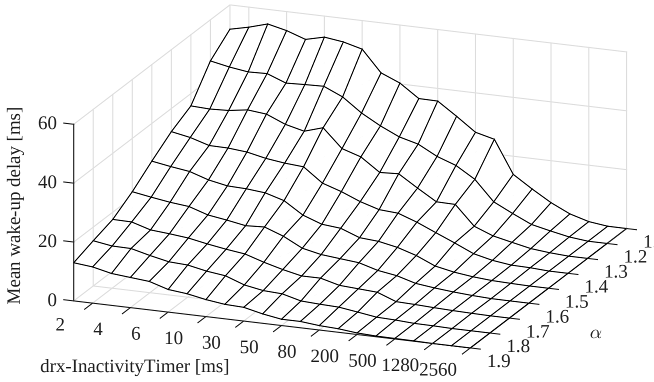

Fig. 17: Case 2, Stage 2 – Mean wake-up delay

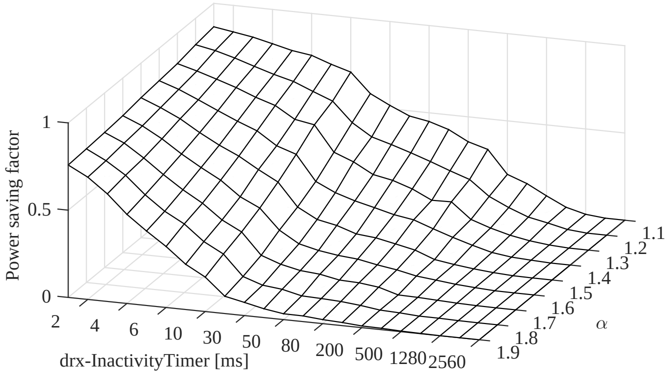

Fig. 18: Case 2, Stage 2 – Power saving factor

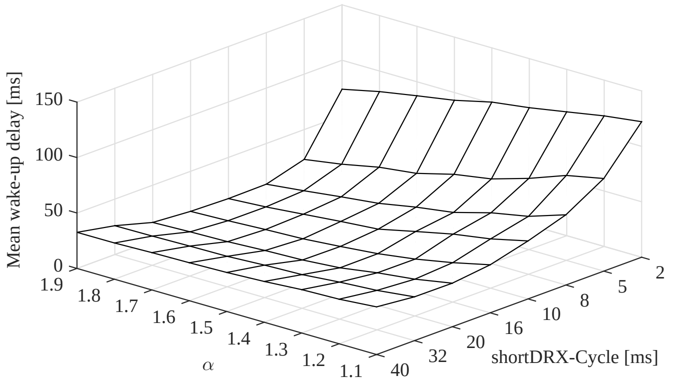

Fig. 19: Case 2, Stage 3 – Mean wake-up delay

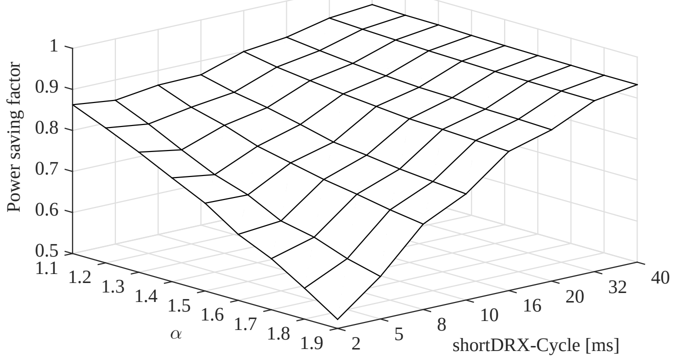

Fig. 20: Case 2, Stage 3 – Power saving factor

Cycle upon the performance metrics when active state is considered (Fig. 19-20) or not (Fig. 13-14), can not be distinguished.

VI. CONCLUSIONS

We have presented probabilistic models to evaluate the Discontinuous Reception Mechanism (DRX) of LTE/LTE-A networks. With a special emphasis on the military training application types of traffic, we have quantitatively characterized the performance of the network in terms of mean wake-up delay and power saving factor.

Our future work will be dedicated to the energy-efficiency management methods, when they are implemented at the base station side.

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Hawar Ramazanali received the Master's degree in electronics design from Linköping University, Campus Norrköping, Norrköping, Sweden in 2006. He is currently an industrial PhD student at Halmstad University and has been working with radio systems at Saab Training and Simulation since 2008.

Alexey Vinel (M'07–SM'12) received the Bachelor's (Hons.) and Master's (Hons.) degrees in information systems from Saint-Petersburg State University of Aerospace Instrumentation, Saint Petersburg, Russia, in 2003 and 2005, respectively; the Ph.D. degree in technology from the Institute for Information Transmission Problems, Moscow, Russia, in 2007; and Ph.D. degree in technology from Tampere University of Technology, Tampere, Finland, in 2013.

He is currently a Professor of data communications with the School of Information Technology, Halmstad University, Halmstad, Sweden. He has been involved in research projects on vehicular networking standards, advanced driver-assistance systems, and autonomous driving.

Dr. Vinel has been an Associate Editor for the IEEE COMMUNICATIONS LETTERS since 2012 and IEEE WIRELESS COMMUNICATIONS MAGAZINE since 2015.