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Jointly Optimizing RRC State Transition and DRX in 5G New Radio

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***Abstract*—This study analyzes the contribution of RRC and DRX procedures to the optimization of the performance of 5G New Radio Access Networks. In particular, we investigate the latency versus device energy consumption trade-off in a standalone 5G environment with multiple traffic profiles and RRC inactivity timers. The investigation results form the basis of an optimization procedure that selects the appropriate RRC state transition parameters according to the users' performance requirements and packet arrival rates.**

***Index Terms*—5G, NR, RRC States, RRC Inactive, DRX, Inactivity Timer, Suspend Timer, Energy Consumption, Latency, Delay, Signaling**

I. Introduction

The deployment of 5G and beyond 5G mobile networks is a global ongoing project that will affect the life of billions of people in the coming years by introducing novel services with differentiated requirements, which will appeal to new types of customers. 5G subscriptions are expected to reach 5.6 billion by the end of 2029 [1]. Industry, transportation, medicine, robotics and other domains will benefit significantly from the emergence of new generation mobile services, such as autonomous driving and tele-surgery, or the enhancement of existing ones, such as ultra-high-speed mobile broadband and massive IoT communication.

The following three main categories of 5G services can be defined, according to their performance requirements:

- Ultra Reliable Low Latency Communication (URLLC) services, which includes tele-surgery, autonomous driving, industry automation, interactive gaming.
- Enhanced Mobile Broadband (eMBB) services, which require very high bit rates (Gbps), such as 3D video and augmented reality.
- Massive Machine Type Communication (mMTC) services, including smart city and telemetry applications.

The different characteristics of the above service categories require a significant enhancement of the New Radio (NR) optimization procedures. The legacy Radio Resource Control (RRC) and Discontinuous Reception (DRX) mechanisms have been enhanced with the introduction of the new RRC Inactive state in 5G network specifications, which can be deployed as an intermediate step with separate DRX configurations, providing additional flexibility and tuning possibilities.

The contributions of this paper are the following:

- We investigate the joint operation of the new 5G RRC state transition and DRX mechanisms in terms of latency, signaling load, and energy efficiency.
- Based on the results from this investigation, we propose a new procedure for optimizing the RRC inactivity timers that tune the state transition procedure, considering each user's traffic characteristics.
- We study the improvements in the energy efficiency gain, when the RRC inactivity timers are defined independently for each User Equipment (UE) or for a group of Users, according to their packet arrival rates.

Our investigation uses a simulation environment that has the following features:

- The simulation program considers data packet arrival profiles based on Poisson processes, with exponentially distributed arrival times.
- The effect of the RRC state transition and DRX mechanisms is simulated, and latency and energy consumption results are produced, for multiple users with different packet arrival rates. The simulation is repeated for a range of configurable RRC inactivity timers.
- Optimal inactivity timer values are proposed for each traffic profile, to optimize energy consumption according to given delay requirements.

II. Related Work

Many studies analyze the effects of RRC state transition and DRX processes on energy consumption and network performance. In [2] the authors study the latency versus energy efficiency trade-off, for discrete packet arrival rates and configuration parameters (DRX cycles and RRC suspend timers). The authors in [3] investigate traffic scenarios and calculate the effects of three possible RRC inactivity timer values. In [4] multi-traffic scenarios are presented for a two-RRC state model, without considering the RRC Inactive state. Recent articles focus on specific aspects, such as signaling load and delay in machine-type communications

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[5], or efficient resource allocation under energy consumption constraints [6], without analyzing the interaction between these metrics and the trade-off that can be achieved with RRC and DRX parameter tuning.

Unlike older studies that consider transitions between two RRC states, our approach investigates the performance of 5G Stand Alone (SA) networks considering a three-state model, with the new RRC Inactive state intervening between RRC Connected and RRC Idle. We include continuous ranges of packet arrival rates and RRC inactivity timers in our calculations, aiming to define dependence relations and to propose an effective procedure for jointly setting the timer thresholds. Furthermore, we study how the behaviour is affected by the number of optimal RRC suspend timers that are defined for a range of traffic arrival profiles.

III. RRC and DRX Procedures in 5G

A. New RRC State Model

The two basic RRC states of the UE, inherited from 4G networks, are “RRC Idle” and “RRC Connected” [7] [8]. A UE in RRC Connected state establishes an end-to-end connection with the Radio Access Network (RAN) and Core Network (CN) nodes, to exchange data packets and send quality and coverage measurements that are essential for the mobility procedures and the maintenance of the required Quality of Service. Due to the variable radio conditions of the active mobile users, robust signaling procedures are required to ensure the connection retain-ability. This has a significant effect in the battery consumption of the UE.

When there are no packets to be transmitted or received, all connection resources are released, and the UE performs a transition to the energy and resource - efficient RRC Idle state (“RRC release” procedure). Idle UEs can select the strongest radio cell from which they receive signaling messages, but they do not transmit information and their exact position is not known to the network. When there are new data packets to be transmitted to the user, the CN performs a paging procedure in a geographical area, called Tracking Area (TA). The paging message is sent to all the gNodeBs that belong to the same TA, to find the radio cell that is selected by the UE. After the UE has responded to the paging message, a new RRC Connection is established (“RRC setup” procedure).

The new “RRC Inactive” state was introduced in 5G Release 15 to form an “intermediate” step between the two legacy states described above [8] [9] [10]. In RRC Inactive state, the CN elements maintain the connection data of the inactive users, by storing UE context and security information, so that no CN signaling is needed when a new data session starts.

The 5G RAN elements (gNodeBs, radio cells) do not maintain the connection with the inactive users. As a consequence, they are involved in paging and control processes, at the beginning of a new RRC Connection (“RRC resume” procedure). RAN paging messages are sent to RRC Inactive UEs by gNodeBs that belong in the same RAN Notification Area (RNA), in a similar way the paging messages to idle users are sent from the Core elements in the TA. Despite of the RAN paging functionality, fewer signaling messages are needed in total (resulting to lower delay), when there is a connection resume from RRC Inactive state, instead of a new establishment from RRC Idle.

The basic processes of the 5G RRC state model are shown in Fig.1. The transition from RRC Connected to RRC Inactive and Idle states is triggered by UE inactivity. After the completion of a data session, an inactivity timer starts. If a data packet arrives before the expiration of the timer, the user remains in RRC Connected state. Otherwise the timer expires and a transition to a “lower” connection-less state is performed. The RRC Inactivity timer is specifically called “Suspend timer” if it triggers a transition from RRC Connected to RRC Inactive state. In case of a transition to RRC Idle state, the RRC Inactivity timer is referred to as “Release timer”.

As stated above, the RRC Inactive state can be beneficial in many ways, as it balances the overhead of the other two states, which are high signaling load and latency when a packet arrives while the UE is in Idle state, and high energy consumption when the RRC Connected State is maintained for long periods of inactivity. Nevertheless, it increases complexity and requires extra CN Resources for the storage of the UE Context and the maintenance of the connection in the CN nodes. A typical NR network configuration would enable a fast energy - efficient transition from RRC Connected to RRC Inactive after the reception of the last packet, with a low suspend timer value, followed by a second (less aggressive) RRC Release to Idle state, if the user remains inactive for a longer period of time (RRC Release timer expiry).

B. UE Energy Saving with CDRX and IDRX

A relative UE energy saving process that is inherited from 4G and can be activated in all 5G RRC States, is Discontinuous Reception (DRX). DRX enables the configuration of

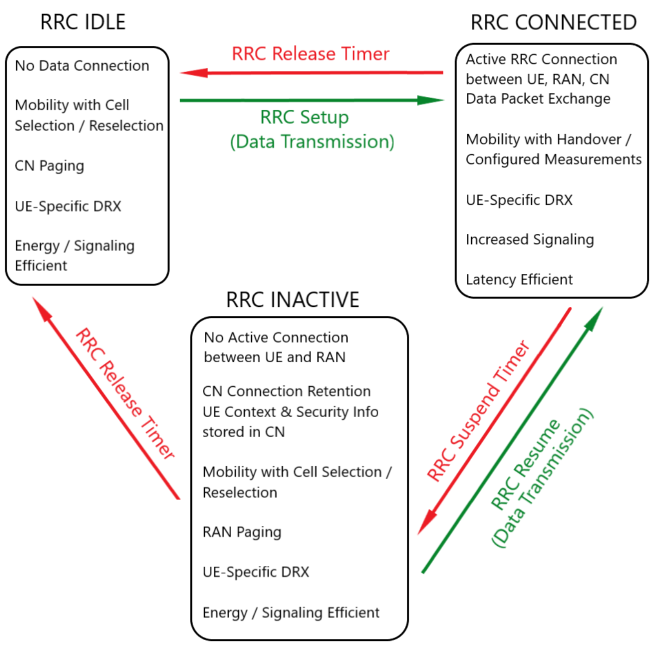

Fig. 1. RRC State Transition Procedures

the UE for "sleeping" and "waking-up" periods, in order to extend its battery lifetime. After the reception of a packet, the UE remains active, waiting for the next packet, for a configurable time period called "DRX inactivity timer". After the expiration of the timer, the UE has the possibility to power down for another period called "DRX cycle" to save battery. Between consecutive DRX cycles, waking-up ("On") periods are configured, during which the UE receives packets and signaling messages. The waking-up period duration is defined by parameter called "On duration timer". [7] [8] [11].

The effectiveness of the DRX process depends on the size of the aforementioned time periods. As the DRX cycle length increases, the UE energy savings improve, but the packet reception delay increases. A network operator can define different cycle lengths ("short" - "long" DRX cycles) depending the last packet reception time. Moreover, different DRX configurations are allowed for the three UE RRC States. The term "CDRX" is used in the RRC Connected state and the term "IDRX" refers to the RRC Inactive and Idle states.

When the UE is in the RRC connected state, CDRX is configured with relatively high DRX Inactivity and On timers to enable prompt reception of the arriving packets. In RRC Inactive and RRC Idle states the IDRX mechanism can be more intense, to improve UE energy efficiency with extended sleeping cycles, at the end of which the UE listens to the paging channel (originated from the RAN or CN respectively). IDRX cycles are often referred as "Paging cycles" (especially when the UE is in Idle state).

IV. Simulation Model

Having the intention to study the effects and the interaction of RRC state transition and DRX procedures, we created a prototype Python simulator that implements these procedures in the NR - UE environment. This section describes the main characteristics of the simulated system, shown in Fig.2.

Table I shows the basic simulation parameters, whose values are based on 5G RAN best practice configurations and on settings described in related reference publications [2] [12].

Each user's traffic profile is simulated by a Poisson process with mean rate λ. The probability distribution of the time interval between two consecutive packet arrivals is exponential, with mean inter-packet arrival time = $1/\lambda$. A procedure that generates data packets with rates that follow each user's inter-packet arrival time distribution is the input to the simulator.

The main simulated processes are summarized below.

1) If the time interval until the next packet reception is lower than the suspend timer value, the packet will arrive while the user is still in RRC Connected mode. If additionally the packet arrives before the CDRX inactivity timer expires or during a waking-up ("On") period (parts marked with blue in Fig.2), it is immediately received by an active UE and the delay is minimal (2.85ms according to Table I). If the packet arrives during a CDRX sleeping cycle, there will be an additional reception delay, until the next On period.

2) If the packet arrives later than the expiration of the suspend timer, it is received after the UE has performed a

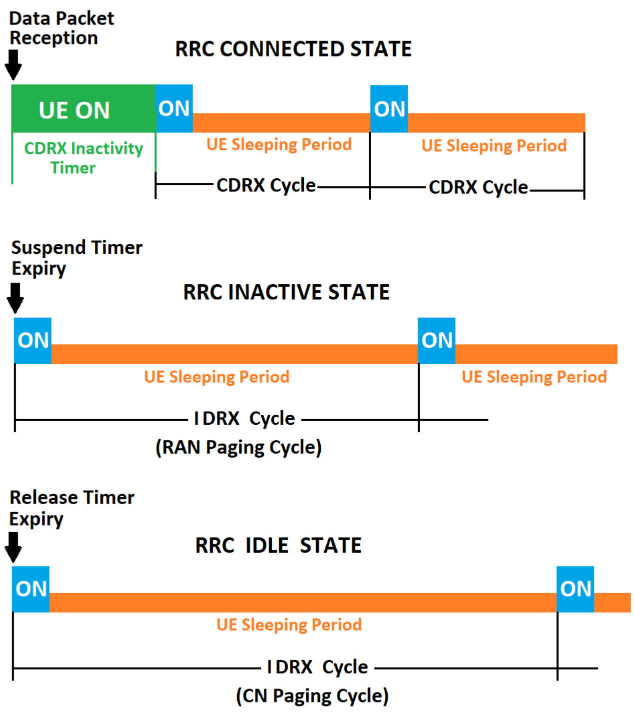

Fig. 2. Simulated UE Behavior

transition to the RRC Inactive state, which has a longer IDRX cycle than the CDRX. In this case, the delay is the sum of the time between data arrival and the next On period and the additional RRC resume delay for the transition to Connected state (14ms in Table I [2]). A similar behavior is simulated in Idle state (when the packet is received after the RRC release timer expires), which has the longest IDRX (paging) cycle and the highest connection establishment delay of all three states (76 ms in Table I [2]).

3) The UE energy consumption depends on the time spent in each RRC state, multiplied with the corresponding power. As shown in Table I, in accordance with [12], a UE typically consumes 48mW of power during RRC Connected "On" periods. In RRC Inactive and Idle "On" periods, the consumption is 20mW. During sleeping periods in all three states, the power consumption is the minimum (0.01mW). Additional power is consumed for the transition to the RRC Connected state, when a packet arrives in Inactive or in Idle state (0.64mW for RRC resume and 1mW for RRC setup respectively). If the packet arrives while the user is already in RRC connected, the signaling power consumption is only 0.04mW.

4) The simulated suspend timer values are lower than the corresponding release timers, to ensure that the unconnected UE will remain in the RRC Inactive state for an acceptable period of time, before making a second transition to RRC Idle. As the suspend and release timers increase, fewer RRC state transitions occur, the user latency decreases, and the energy consumption increases. For very high RRC inactivity timers, the UE always receives packets while in the RRC Connected state, with maximum energy consumption and

TABLE I
SIMULATION PARAMETERS

Traffic Profile	Mean Inter Packet Arrival Time	1 to 60 s
	Packet Size	5 Mbytes
	Radio Cell Capacity (DL Speed)	1.2 Gbps
RRC Connected State DRX (CDRX)	CDRX Inactivity Timer	100 ms
	On Duration Timer	8 ms
	CDRX Cycle	80 ms
RRC Inactive State DRX	On Duration Timer	8 ms
	IDRX (RAN Paging) Cycle	320 ms
RRC Idle State DRX	On Duration Timer	8 ms
	IDRX (CN Paging) Cycle	1280 ms
RRC Inactivity Timers	Suspend Timer (Fixed Scenario)	1 to 30 s
	Release Timer (Fixed Scenario)	10 to 300 s
Delay Parameters	Delay for Idle to Connected transition (RRC Setup)	76 ms
	Delay for Inactive to Connected transition (RRC Resume)	14 ms
	Delay for a Packet Reception in RRC Connected	2.85 ms
UE Power Consumption Parameters	Power Consumption during ON Periods in RRC Connected	48 mW
	Power Consumption during ON Periods in RRC Inactive/Idle	20 mW
	Power Consumption during Sleeping Periods (all states)	0.01 mW
	Power Consumption for Transition from Idle to Connected (RRC Setup)	1 mW
	Power Consumption for Transition from Inactive to Connected (RRC Resume)	0.64 mW
	Power Consumption for Connection Establishment in RRC Connected	0.04 mW

minimum delay. Energy consumption results are normalized with the maximum value, simulated for the "always RRC Connected" UE. The time and power consumed for the actual packet processing are not considered in the simulation calculations, as they do not depend on the RRC state transition mechanism.

V. SIMULATION RESULTS

In the following subsections we describe the results after the execution of simulations with various inputs, in terms of packet reception rates and RRC Inactivity timers. These results are utilized to optimize the trade-off between latency and UE energy consumption in several traffic scenarios.

A. Common Inactivity Timer values for all User profiles

In our first experiment we consider four UEs, served in parallel by a simulated NR cell, which have Poisson-based traffic profiles with mean inter-packet arrival times ($1/\lambda$) ranging from one second to one minute. Profiles with low values of $1/\lambda$ typically describe intense eMBB and URLLC services, while higher values of $1/\lambda$ correspond mainly to mMTC services. In the following example, we calculate the delay and UE normalized energy consumption for $1/\lambda = 1, 4, 20, 60$s.

The results for the two metrics are shown in Fig.3 and Fig.4, for a continuous range of suspend timers that are the same for all users (0 to 30s). The graphs show that the latency improves and the energy consumption increases for all users,

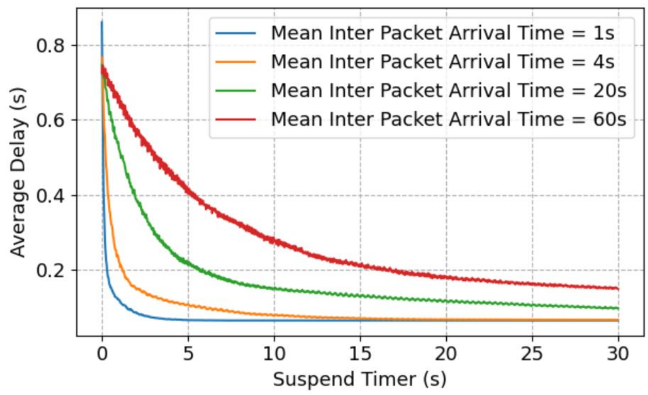

Fig. 3. UE Delay with fixed Suspend Timers

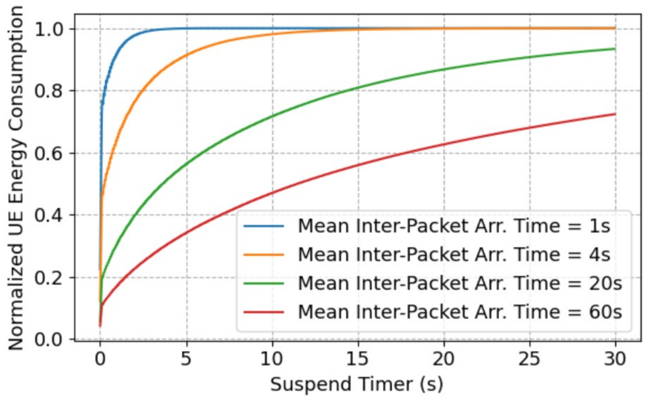

Fig. 4. UE Normalized Energy Consumption with fixed Suspend Timers

as the suspend timer increases and the transition to energy-efficient RRC states is more infrequent.

Nevertheless, the suspend timer dependence is not the same for all UEs. For the same suspend timer, users with higher mean inter-packet arrival times will experience higher latency and lower energy consumption than users with smaller $1/\lambda$, as the former spend more time in energy-efficient RRC states. For example, when the suspend timer is between 2s and 5s there is basically no energy saving for the user with $1/\lambda = 1$s, while the users with higher inter-packet arrival times reduce their consumed energy. The effect of a specific suspend timer value depends on the value of $1/\lambda$.

B. Different Inactivity Timer values, related to the Packet Arrival Rate of each profile

In this subsection we simulate the delay versus energy consumption trade-off, when different suspend timers are applied, according to the characteristics of the users. For each one of the four UEs, the simulation loop applies suspend timers that are proportional to the user's mean inter-packet arrival time.

In Fig.5 the UE delay and normalized energy consumption are shown in the same graph, as a function of the $SuspTimer/MeanInterPacketArrTime$ ratio.

Due to the different mean inter-packet arrival times of each profile, the absolute suspend timer values in the x-axis are not

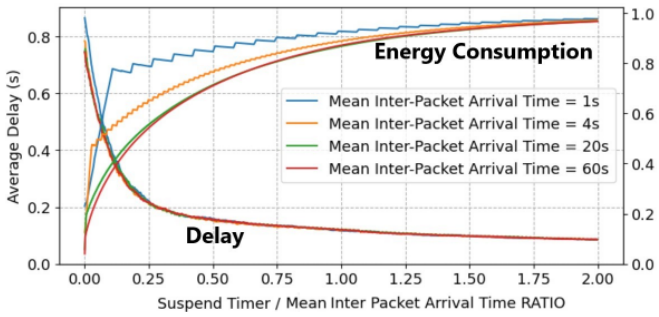

Fig. 5. Average UE Delay and Energy Consumption with fixed "Suspend Timer / Inter-Packet Arrival Time" Ratio

common for the four profiles. For the profile with $1/\lambda = 1$s the simulated suspend timers have a very small range, from 0 to 2s, while the less frequent packet arrival profile ($1/\lambda =$ 60s) is simulated for suspend timers that vary from 0 to 120s. The "saw-tooth" shape of the blue energy consumption line in fig.5 is caused by the effect of the CDRX inactivity timer (100ms) and the periodicity of the CDRX cycles (80ms), which become visible for very small suspend timer values.

The average delay performance for all traffic profiles exhibits similar behavior for the different values of the $SuspTimer/MeanInterPacketArrTime$ ratio. However, this is not exactly the case for the energy consumption. For very low ratios the energy efficiency differs, in favor of the users with high inter-packet arrival times.

The UE with $1/\lambda = 1$s cannot effectively reduce its consumed energy, even if it performs many transitions to the RRC Inactive state, because the frequent packet arrivals will trigger a high number of RRC transitions to Connected state. This "ping-pong" state transition will require additional power, which will eventually counterbalance the savings achieved by the time spent in the RRC Inactive state.

C. Dynamic Energy Efficiency Optimization with specific Latency Requirements

Based on the above simulation results, we define a procedure to optimize the RRC inactivity timers according to the mean inter-packet arrival times, while satisfying the user delay requirements. Specifically, we calculate the appropriate suspend timer values that minimize the UE energy consumption, while maintaining the delay below a predefined threshold. Such an optimization is necessary for URLLC and delay sensitive applications, which can not be deployed if latency exceeds a specified value.

In Scenario A, we assume a maximum acceptable average delay $Dmax = 0.3$s for users with mean inter-packet arrival times ($1/\lambda$) from 0.5 to 60s (in x-axis). For each value of $1/\lambda$, the optimization procedure performs repeated simulations to calculate the delay and energy consumption, for increasing values of the suspend timer. When the calculated delay reaches $Dmax$ the loop stops and the corresponding suspend timer value is the optimum $Sopt$ for the particular traffic profile. The same procedure is applied for the next traffic profile with a different mean inter-packet arrival time. Fig.6 shows that the optimal suspend timer $Sopt$ is approximately proportional to the mean inter-packet arrival time.

In real multi-service environments with diverse user and traffic characteristics, setting the RRC inactivity timers on a "per user" basis might not be feasible. Alternatively, grouping UEs based on their traffic profiles and assigning a single optimal RRC inactivity timer value to each group would be a more realistic approach. Indeed, new network specifications include procedures for UE grouping and classification based on traffic characteristics, service information, and feedback received by the UE itself ("UE Assistance Information" [9]).

Based on the above, in Scenario B we simulate a step-wise quantization process that results in discrete suspend timer values. For each value of $1/\lambda$, the corresponding optimum suspend timer ($Sopt$) calculated in Scenario A is rounded up to the nearest stepped value. The round-up procedure that defines higher discrete suspend timers than $Sopt$ for each traffic profile ensures that the latency requirements are satisfied. Furthermore, as shown in the previous section (Fig.5), very low suspend timer values do not always guarantee energy efficiency, especially for very frequent packet arrivals (small values of $1/\lambda$). In such cases, rounding-up of very small suspend timer values improves the delay with negligible energy consumption cost. Fig.6 shows the rounded suspend timers $Sopt2$, when the quantization step is 2s.

New latency and energy consumption values are calculated per traffic profile, when the suspend timer is $Sopt2$. Fig.7 shows the user delay versus energy efficiency trade-off for both scenarios, as functions of inter-packet arrival times.

The metrics that correspond to the green bar are simulated for $Sopt$ values and the metrics that correspond to the blue bar are simulated using $Sopt2$ values.

While the $Delay < Dmax$ requirement is satisfied for both scenarios, the step-wise attribution is more latency - efficient, as $Sopt2$ is always higher or equal to $Sopt$. This has a negative effect on the UE energy consumption, which increases as the suspend timer increases. Every time the discrete $Sopt2$ value changes to the next higher step, there is a steep delay reduction and a corresponding sharp increase in the energy consumption.

From the above investigation, we come to the conclusion

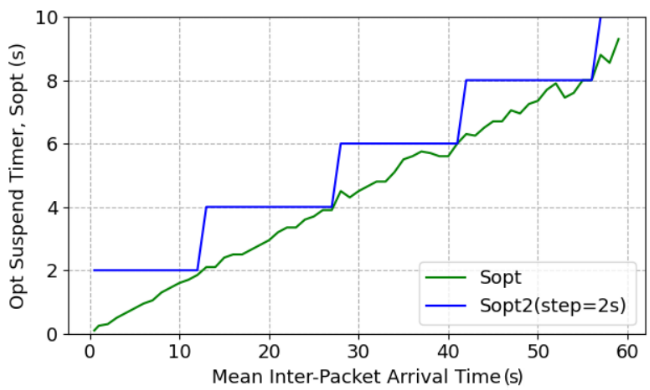

Fig. 6. Optimal Suspend Timers for UE Energy Consumption minimization when $Delay < Dmax$

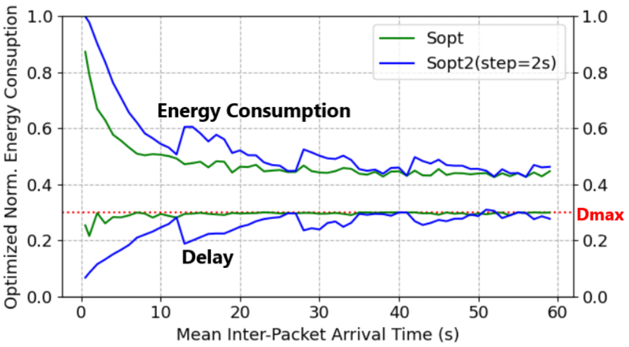

Fig. 7. UE Delay and norm. Energy Consumption for optimal Suspend Timers

that the categorization of the UEs in groups (according to their traffic characteristics) and the relevant quantization of the optimal suspend timers, can reduce the complexity and improve the latency, at the cost of higher energy consumption, in comparison with the continuous $Sopt$ calculation.

In our final experiment, we show the impact of different quantization steps on the UE energy savings. Fig.8 shows the overall average normalized energy consumption for all users when $Sopt$ is continuous, or rounded-up with different steps. The last bar shows the maximum UE energy consumption, which is calculated when the suspend timer has the same value for all users. In the specific scenario we consider, this value has to be at least 10s, to satisfy the constraint $Delay < Dmax$ for all traffic profiles.

The results in Fig.8 show that assigning optimal suspend timers per user achieves 20% additional UE energy savings compared to when the same suspend timer is assigned to all users. When the timer optimization is done in quantization steps, the additional UE energy savings are lower than 20% and depend on the step size. Specifically, our results show that the UE energy savings are reduced to 15% when the optimal suspend timers are rounded up to steps of 2s.

VI. Conclusion and Future Work

We quantified and discussed the contribution of the RRC Inactive and Idle states to UE energy efficiency, as well as the latency benefits when the users remain in the RRC Connected state. The trade-off between delay and UE energy consumption was investigated for a wide range of RRC inactivity timers, in a system with multiple Poisson-based user traffic profiles. We described an energy-efficient RRC inactivity timer optimization procedure in a multi-user network with specific delay requirements. Our results show that optimal RRC suspend timers can provide up to 20% energy savings compared to when the suspend timer has the same value for all users. Finally, we discussed a step-wise optimization process with discrete RRC inactivity timer values assigned to groups of users with similar mean inter-packet arrival times, which is less complex compared to assigning a different inactivity timer to each UE.

Our future work will consider more sophisticated and realistic traffic models (e.g. with 5G-specific traffic classification, [13]) that will enable further analysis and optimization of real New Radio Access Networks. Novel energy saving techniques, such as Bandwidth Part (BWP) and Wake-up Radio (WUR) [11] [12] will also be investigated.

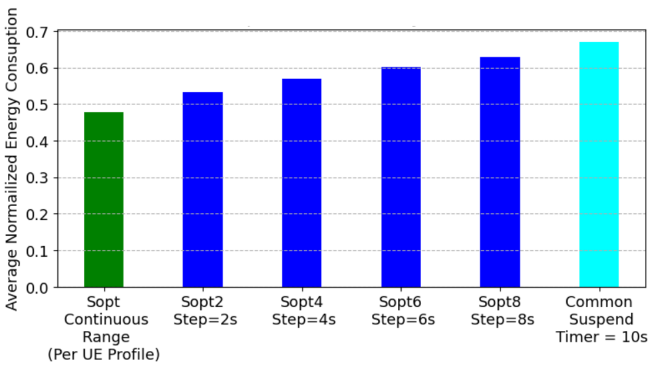

Fig. 8. Overall UE Energy Savings when $Delay < Dmax$, for Continuous and Step-wise optimal Suspend Timers

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