Optimizing DRX for Video delivery over LTE: Utilizing Channel Prediction and In-network Caching

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***Abstract*—We jointly optimize Discontinuous Reception (DRX) cycle length and LTE scheduling to minimize mobile devices' energy usage for video delivery, utilising the now well-established potential to predict future channel conditions in cellular networks. Employing in-network caching, we set a strict buffer constraint which provides zero buffer underflow to improve Quality of Experience. Our study provides insight into the energy saving potential sophisticated DRX schemes hold, compared with the currently used static method. To this end, two novel DRX approaches are proposed and studied. The results show that more sophisticated DRX schemes (with variable DRX cycle length) can potentially save 69 percent energy for mobile devices, encouraging further research in the field.**

***Keywords*—DRX optimization, LTE resource allocation, buffer underflow, bandwidth prediction, in-network caching.**

I. Introduction

By 2021, 4G will account for 75 percent of total mobile data traffic and more than 78 percent of this traffic will be video [1]. Therefore, video streaming over LTE is currently a particularly interesting combination to study. In these networks, fluctuations in channel conditions have a negative impact on performance in terms of data rate, delay and energy efficiency where streaming video services are especially exposed due to stringent performance requirements. Some of the important approaches introduced to deal with energy usage and performance degradation while delivering video over mobile networks include adaptive video bitrate (such as DASH and SVC), in-network caching and Discontinuous Reception (DRX) configuration and optimization.

Joint bitrate adaptation and DRX configuration approaches have been considered in order to enhance performance in terms of energy usage and Quality of Experience (QoE). In [2], the authors tried to adapt DRX parameters and video bit rate to suit varying network conditions. In [3], DRX performance with bursty traffic was analyzed. However, in both papers DRX configuration was based on packet arrivals where buffer underflows are possible. It is observed in [4], that different applications may require different DRX settings. In [5], user equipment (UEs) are scheduled according to the DRX pattern. However, buffer underflows can still happen and their occurrence highly depends on the DRX length. Longer DRX cycles cause longer display interruptions in their proposed method. In [6], DRX was optimized for delay sensitive applications but video was not of particular interest and video stalling still was possible.

There are several performance issues associated with the above approaches. They suffer from video quality degradation under poor network conditions. Moreover, video delivery during poor channel conditions increases reception time. The longer the reception time is, the less sleep opportunity the UE has, and the less efficient DRX becomes. The situation becomes worse when considering packet arrival rate. Without reliable channel and traffic prediction, DRX can become inefficient in terms of delay, QoE, and energy. Long DRX cycles result in unacceptable transmission delay and buffer underflow and short DRX cycles cause unnecessary wake ups whose cost sometimes can be higher than keeping the UE awake.

Recently, in-network caching for mobile networks has attracted much attention. Caching the content close to UEs (i.e. inside the Radio Access Network (RAN)) not only eliminates the energy usage for transferring the data from the video streaming server, but also eliminates packet arrivals as a concern. This then allows for better and more convenient LTE scheduling and DRX configurations. In [7] and [8], potential advantages of caching videos at eNodeBs (eNBs) were investigated in terms of network delay and QoE.

Although in-network caching eliminates the problem of arrival rates and energy usage due to video transmission from the origin server to the UE, wireless channel quality fluctuations is still a serious problem. Prediction of future channel conditions can provide a practical solution to address this problem satisfactorily. The evidence shows that network conditions experienced by mobile devices are significantly influenced by geographical location within the cell [9]. According to the empirical study in [10], future channel rates can be predicted due to the correlation between location and channel conditions. Also, in [11], [12], it is experimentally shown that the future channel conditions of

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mobile users can be predicted up to a certain future time using user location information. From a network operator perspective, being aware of a users future channel conditions allows design of more efficient resource allocation algorithms and provisioning of better QoS. In [13] future channel information is utilized to develop energy efficient algorithms for video streaming but the DRX mechanism is not considered. In a similar study [14], the strong correlation between geographic location and network capacity is exploited to improve QoS of mobile users without considering energy usage. In addition, the authors in [15] optimize the resource allocation and buffer size jointly, by taking advantage of the future channel information. In [16], the feasibility and effectiveness of both future channel prediction and stored videos is exploited for improved QoS of video transmission. However, in [16], energy usage is not considered.

Unlike the aforementioned works, in this paper we aim to address the energy efficiency of UEs with video transmission by optimizing the DRX parameters and scheduling policy of LTE systems and utilizing future channel prediction and video caching in the RAN. It is assumed that future data rates for mobile users are known for a future period. We compare the performance of conventional DRX (which we will henceforth refer to as Static DRX (SDRX)), and two novel DRX schemes called Variable DRX (VDRX) and DRXset in the presence of channel prediction and in-network caching. VDRX allows UEs to utilize any sleep opportunity. This requires modification of DRX parameters more frequently. Considering the signalling overhead associated with changing DRX parameters more often, we introduce DRXset, which incurs less signalling overhead in practice. The DRXset approach utilizes the knowledge of future channel states of the UEs and selects the best DRX cycle length for each UE from a set of DRX cycle lengths. The best DRX cycle length is the one that minimizes the energy usage, and the selected DRX cycles cannot be changed later. Our aim is to minimize energy usage while satisfying smooth streaming with zero buffer underflow.

The remainder of the paper is organized as follows. Section II , explains the three DRX approaches used in this work, as well as the considered reference power model for UEs. Our system model and problem formulation is presented in Section III. Section IV describes our implementation setup and results. Finally, in Section V we conclude this work and outline some future work directions.

II. DRX AND POWER MODEL

DRX incorporates several configurable parameters such as DRX on-duration, DRX inactivity timer, long and short DRX cycle length, short cycle timer, etc. During the on-duration, the UE wakes up and monitors the channel for any incoming data. If there is no data the UE will switch to sleep mode again. Packets that arrive during the sleep time will be buffered in the eNB until the next on-duration. After data reception, the UE starts an inactivity timer to wait for possible delayed data. If no data arrives during the inactivity timer, the UE starts DRX short cycles. The number of short cycles is decided by the short cycle timer. After the short cycle timer expires, the UE starts long DRX cycles [17].

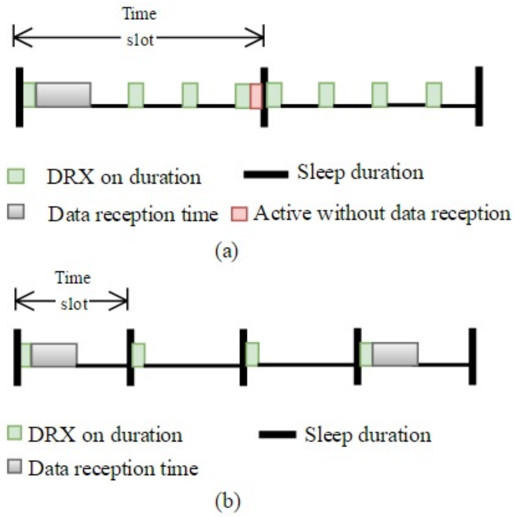

Fig. 1: (a) SDRX and DRXset, (b) VDRX

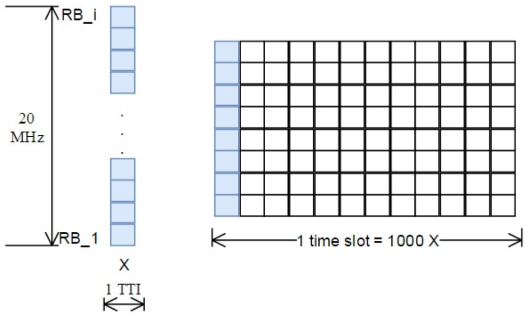

Fig. 2: mini slot and time slot

According to [18], UE can be in four different states: deep sleep, light sleep (short cycle), active with data RX, or active without data RX. DRX parameters related to each state are given in [18]. The UE energy usage is defined as the sum of the energy usage during these states.

$$\sum_{i=1}^{4} P_i t_i \tag{1}$$

where P_i is the power consumption (W) at state i and t_i is the duration of time spent at state i.

Figure 1 illustrates the SDRX and DRXset (a), and VDRX mechanisms (b). In SDRX all UEs have the same constant DRX cycle length, predefined on-duration and inactivity timer. We stress that in this work we assume in-network caching and channel prediction. This assumption is the best case for SDRX because without channel prediction and caching, the eNB needs to consider the packet arrival rate and current channel states to configure DRX, which as we discussed earlier degrades the efficiency of DRX. In this paper, we investigate the potential gains under ideal conditions. In practice, channel prediction is associated with some error and the effects of this is a future research direction as will be discussed in Section V.

In the absence of prediction errors, unnecessarily frequent DRX on-durations and inactivity timers are considered to be a waste of energy. Further, there are situations where the remaining time to the end of a time slot is less than one DRX cycle. In this case, in our proposed schemes, the UE must stay awake even though it is not receiving data. Although this represents another type of waste, it simplifies scheduling and reduces the complexity of the optimization problem. In the following, we refer to this kind of inactive period as waste. By using in-network caching and channel prediction, it becomes redundant to set short cycles or an inactivity timer since we can calculate a sufficient reception time in advance and need not consider new packet arrivals. Therefore these are set to 0. For the same reason we can set the on-duration to 1 ms, as this is the smallest possible value for the on-duration.

In our first proposed configuration, which we call DRXset, DRX cycle length for each UE is chosen from a set of possible values. Figure 1(a) illustrates the DRXset mechanism for one UE. In this case, each UE can be assigned a different DRX cycle length in order to minimize its energy usage. Once the DRX length is chosen, the UE must then keep the same value in all slots.

Our second approach, variable DRX cycle length (VDRX) shown in Figure 1(b), allows UEs to change their DRX cycle length every slot if necessary. This means that at each slot each user can receive data and can then switch to sleep mode for the remainder of the slot. Sleep duration can vary in accordance with the length of the reception time. This reduces unnecessary transitions due to short DRX cycles during the slots when the UE is not receiving data. In addition, this approach, due to its variable length, utilizes all available sleep opportunities.

TABLE I: Notation used in the problem formulation

Notation	Meaning
$\mathcal{C}$	set of users ($c \in \mathcal{C}$)
$\mathcal{S}$	set of time slots ($s \in \mathcal{S}$)
$\mathcal{K}$	set of DRX cycle length indices ($k \in \mathcal{K}$)
$A(c)$	video file size
$H(s,c)$	average capacity of the channel for user c at time s
$D(c)$	video display rate
$Q(c)$	lower threshold of UE's buffer
$E(1)$	energy usage in active state with data rx mode
$E(2)$	energy usage in active state with no data rx mode
$E(3)$	energy usage in DRX mode (ON and transitions)
q_c^0	initial buffer size of user c
q_c^s	buffer occupation of user c at time s
X_c^s	the number of minislots allocated to user c in slot s
Z_c^s	energy waste
m_{ck}^s	the number of DRX cycles for user c in slot s
y_{ck}	matrix of binary decision variable to indicate which DRX cycle length is chosen by each UE
t	the total number of minislots in the slot
τ	DRX cycle length

III. System model and problem formulation

Below we formulate the energy minimization problem. The considered problem setting is as follows (Table I summarizes the notation). The channel prediction window is composed of S (time) slots and each slot $s \in \mathcal{S}$ (where $\mathcal{S} = \{1, 2 \ldots, S\}$ denotes the set of slots) is composed of t mini slots, X_c^s. Figure 2 illustrates the relation between resource block (RB), mini slot, and time slot. As shown in Figure 2 each X_c^s is one TTI in time and 20 MHz in frequency (in this work we consider 20 MHz LTE channel bandwidth.) During each mini slot we allocate all RBs to one user. Therefore if a mini slot is allocated to a user it means that the total number of RBs during that TTI are dedicated to that user. In each time slot either all mini slots or a fraction of them can be allocated to each user, but once a mini slot is allocated to a user, no other users may share it.

Each user $c \in \mathcal{C}$ (where $\mathcal{C} = \{1, 2 \ldots, C\}$ denotes the set of users) is characterized by the following (given) parameters: $D(c)$ — the video display rate rate, $Q(c)$ — the lower bound on the buffer content, $H(s,c)$ — average capacity of the channel for user c in slot s (In this work it is assumed to be known for a while ahead of time and found from location-bandwidth look-up tables present at the service provider.) There are K different DRX cycles, and the duration of cycle $k \in \mathcal{K}$ is specified by $\tau(k)$ (where $\tau(k) \leq t$ and $\mathcal{K} = \{1, 2 \ldots, K\}$ denotes the set of allowable cycles). The data rate R_c^s for user c at slot s is expressed as follows:

$$R_c^s = H(s,c) X_c^s \tag{2}$$

Higher data rates can be achieved either by transmitting during good channel states or by allocating more mini slots (airtime). During each time slot the eNB allocates mini slots to users according to both channel quality and buffer status. The goal is to minimize reception time, which is the most energy intensive part of the energy model (1). The assumptions of in-network caching and channel prediction make it possible for the eNB to transmit enough data during the best channel states and let the UEs sleep until either the next good channel state, or when its buffer becomes empty.

The basic variables to be optimized are X_c^s (the integer variable specifying the number of mini slots assigned to user c in slot s) and y_{ck} (the binary variable selecting the DRX cycle k for user c). Aside from these, the problem formulation makes use of integer variables Z_c^s (the number of mini slots in slot s during which user c is active without data reception), m_{ck}^s (equal to the number of DRX cycles that have taken place for each user c in each slot s; this number is equal to zero if

$y_{ck} = 0$ and can be greater than 0 only for $y_{ck} = 1$), and q_c^s (the buffer occupancy of user c at the beginning of slot s; q_c^0 is a given initial buffer occupancy for user c). The problem is formulated as the following integer program.

$$\min E = \sum_{c \in \mathcal{C}} \sum_{s \in \mathcal{S}} (E(1)X_c^s + E(2)Z_c^s + E(3) \sum_{k \in K} m_{ck}^s) \quad (3a)$$

$$\sum_{c \in \mathcal{C}} X_c^s \leq t, \quad s \in \mathcal{S} \quad (3b)$$

$$q_c^s = q_c^{s-1} + H(s-1,c)X_c^{s-1} - D(c), \quad c \in \mathcal{C}, s \in \mathcal{S} \quad (3c)$$

$$Q(c) \leq q_c^s, \quad s \in \mathcal{S}, c \in \mathcal{C} \quad (3d)$$

$$\sum_{k \in \mathcal{K}} y_{ck} = 1, \quad c \in \mathcal{C} \quad (3e)$$

$$m_{ck}^s \leq \frac{t}{\tau(k)} y_{ck}, \quad s \in \mathcal{S} \quad (3f)$$

$$X_c^s + Z_c^s + \sum_{k \in \mathcal{K}} \tau(k) m_{ck}^s = t, \quad c \in \mathcal{C}, s \in \mathcal{S} \quad (3g)$$

$$X_c^s, Z_c^s, q_c^s \in \mathbb{Z}_+, c \in \mathcal{C}, s \in \mathcal{S}; y_{ck} \in \mathbb{B}, c \in \mathcal{C}, k \in \mathcal{K}; \quad m_{ck}^s, c \in \mathcal{C}, k \in \mathcal{K}, s \in \mathcal{S}. \quad (3h)$$

The objective (3a) is to minimize the total UE energy usage, E, during reception (the first term), active with no reception (the second term, considered as waste), and DRX cycles (the third term). We assume that the energy used during on-duration and transition between different states is included in $E(3)$. Constraint (3b) ensures that the total number of mini slots (airtime) dedicated to the user c in slot s does not exceed t. Next, equation (3c) defines (recursively) the buffer occupancies at the beginning of consecutive slots, while inequality (3d) prevents q_c^s from falling below $Q(c)$. This constraint forces the eNB to transmit data to users whose buffer is very close to $Q(c)$, even if they do not have good channel conditions. The eNB can avoid this situation by filling the buffer when the channel state is good and making sure that the transmitted data is enough for the buffer to last until the next good channel state. This means that neither the eNB nor the UE have to waste energy by transmitting under bad channel conditions.

While managing the buffer, the eNB should also decide on the best DRX cycle length that maximizes energy saving. Constraint (3e) indicates whether or not DRX cycle k will be used by user c, and inequality (3f) allows m_{ck}^s, the number of DRX cycles that have taken place for user c in each slot s, to be greater than 0 only for the (unique) cycle k selected by $y_{ck} = 1$. This part is a general formulation for all three DRX approaches. Of course, in SDRX and VDRX there is no y_{ck}. Also, in VDRX, only one DRX cycle happens in each slot. Finally, equation (3g) ensures that reception, waste, and DRX durations for each user sum up to the slot duration.

IV. Implementation and Results

Optimization problem (3) was solved by means of AMPL using the CPLEX integer programming solver. Table II summarizes the implementation parameters used.

TABLE II: Parameters used in the implementation

Parameter	Value
C	10,20,30
K	5
$A(c)$	large enough to last for all slots
$H(s,c)$	uniformly distributed among UEs
$D(c)$	400 kbps, 750 kbps, 1.2 Mbps, mix bitrate
$Q(c)$	equal to $D(c)$
LTE bandwidth	20 MHZ
number of RBs	100
$E(1)$, $E(2)$, $E(3)$	0.5,0.255,0.3 (J/s)
S	240 slots
t slot duration (ms)	1000 ($T = 240$ seconds))
τ DRXset (ms)	10, 50, 100, 500, 1000
τ SDRX (ms)	100
q_c^1	$2D(c)$
UE type	Cat. 3

The scenario assumes a single LTE cell with one eNB and that the average channel capacities $H(s,c)$, $s \in \mathcal{S}, c \in \mathcal{C}$, are known for a while ahead of time. The time slot duration t is thus set to match the channel coherence time, during which average channel capacity does not change significantly. This will be different for different users moving at different speeds. A typical value of t for a vehicle speed of 72 km/h is 1 second [19]. If the users move slower, there is no harm in updating the information more frequently, while higher values of slot duration could result in missing scheduling opportunities. We therefore set t to 1 second. Channel prediction window size is set to 240 time slots (seconds) which is a reasonable size to run the optimization problem.

We solved the problem for different numbers of UEs and video bit rates. The video bit rate is one of the parameters that define how long the buffer can last and when the UE needs to receive data. The SDRX cycle length is set to 100 ms, which is a commonly used value in the literature [20]. In DRXset we consider 5 DRX cycle lengths varying from 10 to 1000 ms, including 100 ms, which is equal to the SDRX cycle length. The complexity increases with the size of this set. We set the lower threshold of the buffer, $Q(c)$, to the video bit rate, $D(c)$.

Figure 3 shows the mean energy usage for different video bit rates for 30 UEs, with 95 percent confidence intervals. Due to space limitations, we do not show the other cases tested. The energy usage reduction is the same for 10 and 20 UEs, except for the reduction between SDRX and DRXset for 750kbps and 1.2Mbps, and mixed bit rate. The difference is due to the optimality gap. The results for VDRX and SDRX are within a 2 percent optimality gap. For DRXset, for 30 UEs, the results are within a 15, 15, 10, and 5 percent optimality gap for mixed bitrate, 1.2 Mbps, 750 kbps, and 400kbps respectively. Therefore the reduction ratio for these 3 cases is slightly less

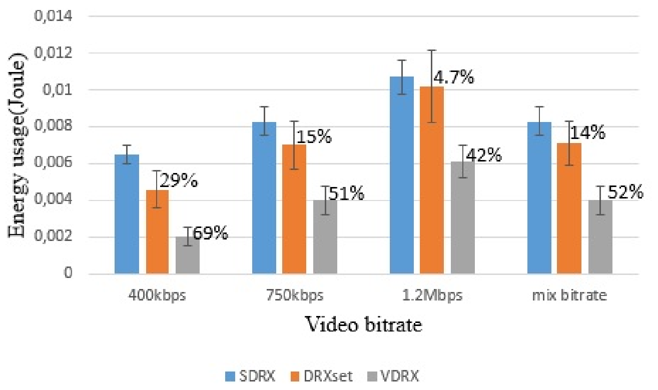

Fig. 3: 30 UEs- energy usage and percentage of energy usage reduction compared to SDRX

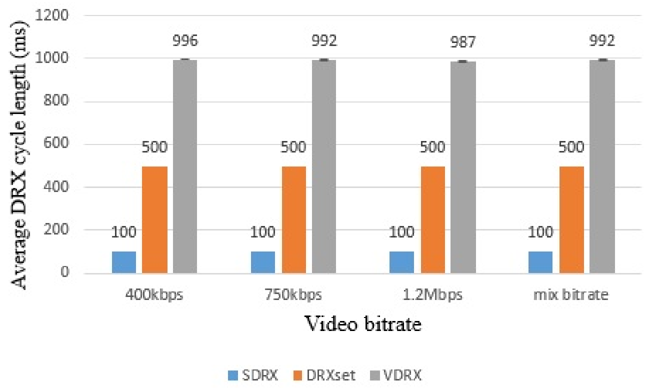

Fig. 4: Average DRX cycle length chosen by three approaches (30 UEs)

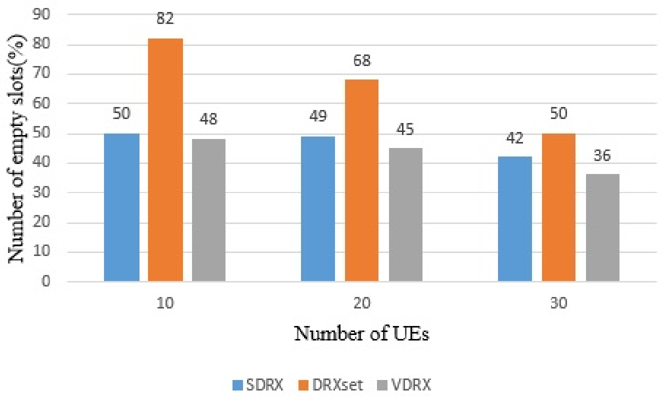

Fig. 5: Percentage of eNB airtime saving(1.2Mbps)

than what we observed in the 10 and 20 UEs cases. This can be improved for 30 UEs by solving the problem to optimality. The optimality gaps are set due to the memory limit on the system that we used to run the solver. With more powerful systems, all cases can be solved to optimal. It should be mentioned that in all cases VDRX and SDRX were much faster than DRXset. This is because in SDRX there is only one DRX length and in VDRX the sleep duration is calculated simply by subtracting reception time from the slot duration.

The initial buffer is set to $2D(c)$. Therefore we have to allocate some resources to each UE no later than the second time slot. When the number of UEs increases, the scheduling in the first couple of slots is not intelligent enough, so that some UEs may miss one sleep opportunity (one DRX cycle). However the effect of this problem in our results is less than 1 percent since it can only happen in the first two slots.

As shown in Figure 3 (and is also the case for 10 and 20 UEs), VDRX outperforms DRXset and SDRX in terms of energy saving in all scenarios. Although the mean energy usage of DRXset is shown as lower than SDRX, in some cases these two approaches have overlapping confidence intervals. However, VDRX is certainly decreasing energy usage significantly. In fact, although DRXset may be easier to implement due to lower signaling overhead, these results show that VDRX is much more efficient and may thus be worth this overhead cost. Besides which, the computational complexity of DRXset is much higher.

Figure 4 shows the average DRX cycle length for our two proposed approaches compared to SDRX. The bars show that when it is allowed to have a variable DRX cycle length, longer cycles are preferable. In the case of DRXset, in all scenarios 500 ms was chosen as the optimal value. This is reasonable because larger cycle lengths result in larger waste (when the remaining time to the end of the slot is less than a DRX cycle and the UE has to stay awake without data reception), while a shorter cycle causes unnecessarily frequent wake ups during the slots with no reception.

By utilizing the knowledge of future channel conditions, our optimization problem minimizes the energy usage on UEs by scheduling them during their best channel conditions and otherwise letting them sleep. The scheme also has two other important effects. First, by putting transmission during the best channel states for each UE, the eNB resources are occupied for less time. In other words, the optimization problem releases resources more frequently, which increases cell capacity. In addition, energy usage on the eNB is also reduced because UEs need resources less frequently. Figure 5 shows the percentage of empty slots during which no UE receives. These times can be considered as eNB airtime (energy) saving.

These results are surprising because one may think that VDRX should be more efficient in terms of airtime saving. Better performance of DRXset in this case occurs because our proposed approaches manage the buffer and energy at the same time. If a UE is about to experience buffer underflow it needs to receive data even though the channel is going to improve in the following slots. In this situation, VDRX due to its flexibility allows a UE to receive only as much data as needed in order for the buffer to last until a good channel state. The UE can then switch to sleep mode for the rest of the slot.

In contrast, using DRXset, short reception times can result in large time waste. For instance, if the UE receives data for 200 ms and the DRX cycle is 500 ms, the UE will experience a waste of 300ms. Therefore it is more energy efficient to send more data when the UE is scheduled (due to its buffer limit or other constraints) even if the channel will be better in the upcoming time slots. This is why VDRX saves more energy, but DRXset uses fewer slots.

It is also worth mentioning that channel state is usually reported to the eNB by the user through channel quality indicator (CQI) reports for one TTI or one specific resource block. Each CQI report is associated with a delay of around 8 TTIs [21]. It is shown in [22] and [23] that CQI delay can greatly affect resource scheduling and throughput. Nonetheless, as discussed earlier the average capacity of the channel can be assumed to be constant during each time slot. Therefore, we consider average capacity of the channel for a whole slot and not at each TTI. At each scheduling time, the large number of mini slots allocated to each UE compensates for the possible channel variation from one TTI to another.

V. Concluding remarks and future work

Due to the fast growth of mobile traffic and video applications over mobile networks, it is important to investigate energy usage and QoE together. In-network caching and future channel prediction can make it possible to have higher video quality with lower energy usage. In this work, DRX cycle length and LTE scheduling were jointly optimized to minimize the UE energy usage while delivering video in the presence of channel prediction and in-network caching. Two novel DRX schemes were proposed and compared to the conventional SDRX. Our results show that VDRX outperforms DRXset and SDRX in terms of energy saving, while DRXset is better in terms of eNB airtime saving. Moreover, DRXset is a more computationally complex algorithm than VDRX but easier to implement due to fewer signalling issues. However, VDRX reduces energy usage up to 69 percent and therefore it may be worth the signalling overhead. In this work zero buffer underflow was achieved by our optimization model. In other words, we showed that by using channel prediction and in-network caching we can save up to 69 percent of UE battery life while also taking care of eNB airtime saving and zero buffer underflow.

There are several possible future directions based on this work. In the extension of this work we will present a heuristic to dynamically optimize DRX cycle length and resource allocation by considering only a few slots ahead of time. Considering channel prediction errors is also of particular importance. Also, more intelligent buffer management approaches are needed to dynamically adapt the upper threshold of the UE's buffer according to the user's watching behavior. The idea here is to store less video in the buffer for users who tend to watch partial video clips more frequently. With regards to in-network caching, content placement optimization and inter-eNB cooperation in the presence of channel prediction are also interesting research directions. Channel prediction can also provide feedback to DASH servers to adapt video bit rate according to the upcoming data rates more efficiently. This in turn results in the potential for more efficient DRX configurations with buffer constraints.

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