Bundling Frames to Save Energy While Streaming Video from LTE Mobile Device

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ABSTRACT

It is becoming feasible to stream user generated video directly to the Internet, which enables a new class of exciting applications and services. However, energy consumption of smartphones that transmit the content over mobile network is a limiting factor. We study the potential of frame bundling to save energy while streaming video through a LTE uplink. Our simulation results show that if real-time streaming is not strictly necessary, bundling video frames for a few seconds before transmitting them is an effective mechanism to save energy. We analyze the energy savings achievable for different video bit rates with varying network conditions, namely round-trip time (RTT), packet loss, UE mobility, and background traffic. The results confirm that bundling remains effective also in non-ideal network conditions.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: [Wireless communication]; H.4.3 [**Communications Applications**]: Computer conferencing, teleconferencing, and videoconferencing; C.4 [**Performance of Systems**]: [Design studies]

General Terms

Algorithms, Design, Experimentation, Measurement, Performance

Keywords

video streaming, LTE, DRX, DTX, energy consumption, energy saving, frame bundling

1. INTRODUCTION

Being able to stream video data near real time from consumer devices over wireless mobile networks opens up possibilities for vast amount of new applications[1]. An interesting example is the Google Glass project the outcome of which will make it possible to share what you see with others through dedicated services. Video from the Google Glass can be transmitted over WiFi or bluetooth to the User Equipment (UE). LTE and its upcoming follow-up LTE-Advanced are promising candidates given the amount of uplink bandwidth they can offer compared to current 3G technologies. However, the energy consumption of radio communication is a concern with today's mobile devices that have a seriously limited battery capacity compared to the computing, communication, and sensing capabilities they offer.

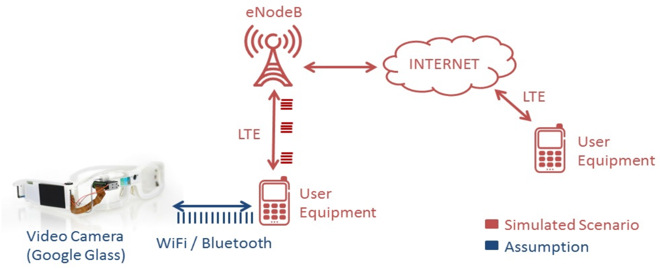

Figure 1: Target scenario

In this paper, we study how much bundling video frames prior to transmission can save energy of the LTE UE while streaming video over the LTE uplink. The scenario is depicted in Figure 1. The video camera transmits the stream to an LTE mobile device that acts as a gateway. If the video frames are transmitted while generated, the LTE radio will be continuously on. However, if the video frames are bundled for a few seconds to a larger burst of data before transmission, the LTE radio can leverage the in-built power saving mechanisms, namely discontinuous reception/transmission (DRX/DTX). In this paper, we show through simulations how much energy can be saved in this way.

Many studies on the energy consumption of mobile devices and how to optimize it have been already conducted, especially in the context of Wi-Fi and 3G communication. For example, Chandra et al. were among the first to study mobile device energy savings using server side traffic shaping[4] and Balasubramanian et al. measured the energy of 3G communication[2]. Hoque et al. investigated different video stream delivery mechanisms from the energy consumption perspective [8], surveyed energy efficient mobile streaming[7], and studied the impact of streaming traffic bundling on the energy consumption [6, 10]. A few papers have studied LTE: Huang et. al[9] and Dusza et. al[5] both measured the energy efficiency of LTE communication. A commonality between all these papers is their focus on downstream communications, whereas our focus is on upstream video transmission over LTE.

Our simulation results reveal that bundling is highly effective way to save energy and that only one second of bundling is enough in some cases to cut the energy consumption to half. Video bitrate has a clear impact on the energy savings achievable so that high

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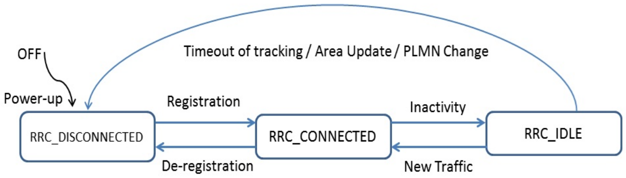

Figure 2: States of LTE UE

bitrate videos provide a smaller opportunity for savings. We also study the impact of network characteristics on the energy savings, namely round-trip time (RTT), packet loss, mobility, and cross-traffic. The results confirm that while all of these have a negative impact on the energy savings, the impact is relatively small with realistic scenarios.

2. BUNDLING FRAMES TO SAVE ENERGY

2.1 LTE power consumption

Figure 2 sketches a state diagram of a LTE UE. When the device is powered on and reachable, the possible states are RRC_CONNECTED and RRC_IDLE. In the former state, the UE has a Radio Resource Control (RRC) connection established with the eNodeB. In that mode, if DRX/DTX is not used, the UE listens to every sub frame and continuously draws a significant amount of power. With DRX/DTX activated, the UE monitors the subframes only during the specified timer intervals. With DTX, after the data is been transmitted the UE turns off the TX circuit and checks for availablity of new data to be transmitted periodically. Similarly, once DRX is activated and if there are no packets received for a long enough duration, i.e. the RRC_Inactivity timer expires, the UE transitions to the RRC_IDLE state in which the UE draws comparatively little power because it only wakes up periodically to receive control sub-frames. Inactivity timer value is set by the network operator with a typical value of 10 seconds[9], which means that the UE typically consumes constantly high power for 10 seconds after completing a data transmission. This energy wasted is sometimes referred to as tail energy and it also exists in 3G networks[2].

Connected mode DRX (cDRX) helps reduce the tail energy in the RRC_CONNECTED state, similar to the RRC_IDLE state. cDRX parameter configuration is network operator controlled and the most important parameters are illustrated in Figure 3.

When there is no data transmission or reception for a certain period of time (Inactivity timer), the UE enters the DRX cycle phase during which the UE periodically monitors the PDCCH only for the *on duration* parameter specified amount of time at each cycle. In this way, the RF circuitry can be switched off in between the DRX cycles and energy is saved. There are short and long DRX cycles. The short cycle is active for a time period specified by the *short DRX timer* after which the UE switches to long cycle. When the long cycle is active, the wakeup interval of the UE is less frequent than during the short cycle. Table 1 summarizes the different roles and typical values of the various LTE timers.

2.2 Video frame bundling with LTE

Figure 4 illustrates what happens when streamed video frames are directly transmitted over the LTE access from the UE to the eNodeB. We assume TCP as the transport protocol and a CBR video source which generates a frame at constant intervals. Each frame is delivered separately to TCP which pushes them through the stack in individual TCP packets.

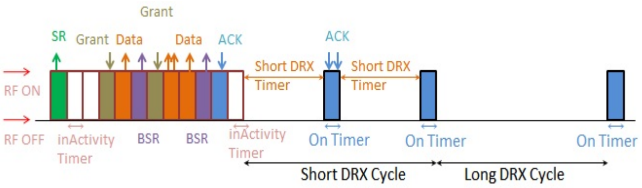

Figure 3: LTE DRX

Parameter	Role	Typical value
DRX on duration (T^{on}_{drx})	wake up duration	1-10 ms
DRX inactivity timer (T^{i}_{drx})	idle time before DRX activation	1-10 ms
short DRX cycle (T^{s}_{drx})	short DRX wake-up interval	10-50 ms
short DRX timer (T^{sc}_{drx})	switch to long cycle on expiry	50-200 ms
long DRX cycle (T^{l}_{drx})	long DRX wake-up interval	50-2560 ms
RRC inactivity timer (T_{RRC})	switch to idle mode on expiry	10000 ms

Table 1: Parameters of DRX enabled LTE.

Once a packet is pushed to the radio link layer, the UE sends a Scheduling Request(SR) and waits for a grant from the eNodeB. On reception of the SR, the scheduler at eNodeB allocates a resource block for the UE and sends a grant to it. Then, the UE transmits data along with a buffer status report (BSR) stating the amount of data in its buffer waiting to be transmitted. The eNodeB provides further grants if needed until the BSR states that the UE has no further data to transmit. Hence, the number of SR messages sent depends on the arrival time of the frames to the Physical layer. If the frames arrive just after the UE has sent data and a BSR with NULL data at buffer, then the UE needs to send a new SR. This process does not allow DRX to operate effectively and leads to high energy consumption.

Instead of directly transmitting each video frame, we propose bundling them by buffering the generated frames for a period of time before transmission. The idea is simple: a timer T_b specifies a bundling period during which frames are buffered. After expiry, buffered frames are sent as a bundle and a new bundling period starts.

2.3 Why bundling saves energy

Figure 5 illustrates what happens when video frames are bundled for period of one second. There are three reasons why bundling saves energy: 1) smaller signaling overhead 2) less overhead due to packet headers, 3) less tail energy. 1 is acheived because frames are sent in continuous batch. Less frequent transmission makes 3 acheivable. On analyzing real-time video transmission in LTE we found out that 2 can be acheived only if frame size is smaller than TCP's maximum segment size (MSS). Hence, lesser the bitrate, higher are the savings through 2. We now briefly study the impact of bundling in analytical manner.

We model the average power draw during a bundle period. Note that this power will be the same as the average power over the whole duration of the video since identical bundling periods follow one after the other. If frames are not bundled, bundling period is equal to transmitting a single frame, i.e. the period is equal to the inverse of the frame rate.

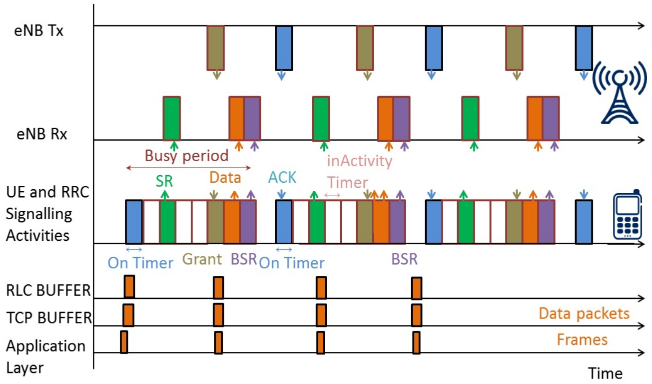

Figure 4: Data transmission without bundling

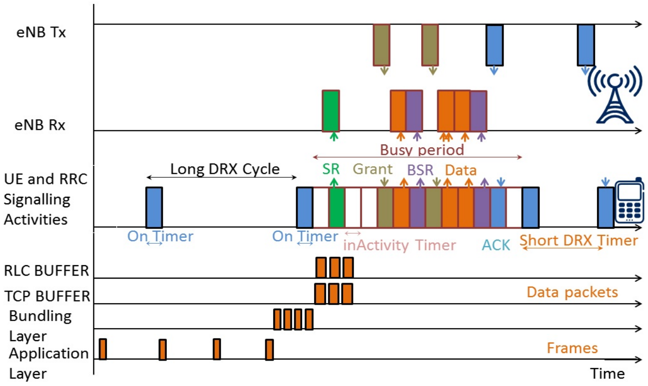

Figure 5: Data transmission with bundling

parameter	value range	description
r_f	30 fps	frame rate
MSS	1460 B	max segment size
w_1	3	init cwnd size
γ	1.5	cwnd increase rate per RTT
C	20 Mbps	LTE uplink capacity
r_s	250-1000 kbps	stream encoding rate
T_b	0-30 s	bundling period
t_{rtt}	5-150 ms	round-trip time
P_{rx}, P_{tx}	1.5 W	rx/tx power
P_s	0.1 W	sleep power

Table 2: Parameters

For simplicity, we only consider the case of no packet loss where TCP will stay in slow start mode during transmission of entire bundle. Our modeling follows [3] where the congestion window growth is approximated using geometric progression formed by subsequent rounds of transmission of congestion window worth of packets. Resulting transmission delay is computed as the number of these rounds times the round-trip time (RTT). We assume that congestion window is reset to its initial value in between bundle transmissions but not in the case when bundling is not used (min bundling period is 1s which is many times longer than the RTT used). Parameters used are described in Tables 1 and 2.

In case the bundle size is large enough to completely saturate the path, i.e. congestion window grows larger than the bandwidth delay product of the path, TCP will continuously transmit and does not need to wait for incoming acknowledgments. Hence, we treat two cases separately depending on whether this happens or not. This condition is expressed in (1) and derived from the geometric progression by solving the number of rounds required to transmit the entire bundle worth of packets (left side of inequality) and to grow the window beyond bandwidth delay product of the path (right side of inequality).

$$\frac{r_sT_b(\gamma-1)}{MSSw_1}+1 \leq \frac{Ct_{rtt}\gamma}{MSSw_1} \tag{1}$$

We then obtain (2) for the time it takes to transmit the data of a single bundle depending on whether the path gets fully saturated during transmission or not.

$$\text{If (1) true: } T_{tx} = log_\gamma\left(\frac{r_sT_b(\gamma-1)}{MSSw_1}+1\right)t_{rtt} \tag{2}$$

$$\text{If (1) false: } T_{tx} = \left[log_\gamma\left(\frac{Ct_{rtt}}{MSSw_1}\right)+1\right]t_{rtt} + \frac{r_sT_b - \frac{MSSw_1 - Ct_{rtt}\gamma}{1-\gamma}}{C}$$

Using this time, we compute the energy spent on transmitting a bundle of frames according to (3). We ignore the impact of receiving the TCP ACKs because of their small size and the fact that they interleave with the transmission of the data packets. We also assume that DRX does not trigger in the middle of bundle transmission (idle time in between TCP flights is shorter than the inactivity timer). The second term corresponds to energy spent on signaling prior to the actual data transmission (t^{eB}_{rtt} is the RTT from the UE to the eNodeB) and the tail energy before DRX is activated.

$$E_{tx} = T_{tx}P_{tx} + (t^{eB}_{rtt} + T^{i}_{drx})P_{rx} \tag{3}$$

In addition to the energy spent in uploading the bundle, the UE spends some energy in between transmitting bundles while DRX is active and while sleeping, which we calculate according to (4). The conditionals take into account whether the idle time in between bundle transmission is long enough for transition from short to long DRX cycle.

$$T_{idle} = T_b - (T_{tx} + t^{eB}_{rtt} + T_i) \tag{4}$$

$$\text{If } T_{idle} \leq T^{sc}_{drx}: E_{drx} = \frac{T_{idle}}{T^{s}_{drx}}T^{on}_{drx}P_{rx}$$

$$E_{sleep} = (T_{idle} - \frac{T_{idle}}{T^{s}_{drx}}T^{on}_{drx})P_s$$

$$\text{If } T_{idle} > T^{sc}_{drx}: E_{drx} = \left(\frac{T^{sc}_{drx}}{T^{s}_{drx}} + \frac{T_{idle} - T^{sc}_{drx}}{T^{l}_{drx}}\right)T^{on}_{drx}P_{rx}$$

$$E_{sleep} = \left(T_{idle} - \left(\frac{T^{sc}_{drx}}{T^{s}_{drx}} + \frac{T_{idle} - T^{sc}_{drx}}{T^{l}_{drx}}\right)T^{on}_{drx}\right)P_s$$

The average power consumption over a bundle period ($\overline{P}_b$) is finally obtained by dividing the sum of E_{tx}(3), E_{drx}(4), and E_{sleep}(4) with the bundle period T_b. Figure 6 plots the average power consumption calculated using the developed model for 500kbps stream ($t_{rtt} = 50ms$, $t^{eB}_{rtt} = 10ms$, $T^{on}_{drx} = 1ms$, $T^{i}_{drx} = 1ms$, $T^{s}_{drx} = 20ms$, $T^{sc}_{drx} = 100ms$, $T^{l}_{drx} = 50ms$). The results suggest that the energy savings using bundling are potentially significant. The sawtooth pattern visible in the plot is due to the fact that TCP sends

Parameter	Value
Simulation time	500.00 s
Nb of base stations/cells/users	1/3/1
Cell radius	166.66 m
UL/DL bandwidth	5 MHz
UE speed	static UE
Environment and parameter model	3GPP Typical Urban
Uplink Capacity	20 Mbps
Video bitrate	250-1000 kbps
Video framerate	30 fps

Table 3: Simulation Parameters

packets in flights of the current congestion window size. Hence, a step up in curve when increasing the bundling period means that there is one packet left over to be sent in a new flight.

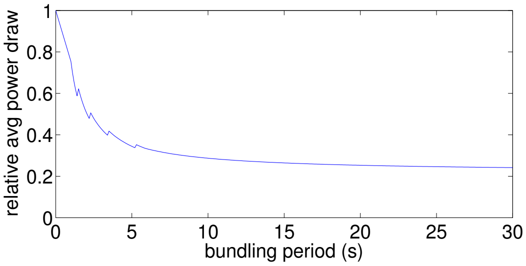

Figure 6: Model-based avg power when bundling.

3. METHODOLOGY

To get a more detailed understanding of the energy saving potential of bundling in various conditions, we conducted a simulation study using a real time simulator. We chose to use simulations because we cannot control the different LTE parameter values and number of simultaneous clients in a commercial network. The simulator implements a complete protocol stack including TCP/IP protocols. The application layer protocol generates CBR video frames. In addition, the simulator implements a complete LTE system and models the wireless channel, intra and inter-cell mobility, and the energy consumption of the UEs.

The scenario for simulation is as illustrated in Figure 1. We exclude the data transmission from the video camera (e.g. glasses) to smartphone and only study the transmission from the UE to the clients using the LTE access network. The parameters used in the simulations are shown in Table 3. We varied a number of parameters during the simulations, such as the video bitrate, UE mobility, packet loss in the Internet, RTT, and amount of cross traffic. The video parameters were inferred by extracting the average bitrate and frame rates for different qualities (240-1080p) of popular YouTube video clips. Each particular scenario was simulated 200 times with two UEs (video stream producer and consumer) created on random locations within a cell each time to ensure that the results are unbiased by the location of the UE. All results presented are averages over the 200 samples.

4. SIMULATION RESULTS

4.1 Impact of DRX configuration

We first looked at effect of DRX configuration and, specifically, the different long and short cycles. We noticed that bundling does not bring impressive energy savings if DRX is disabled. In fact, notable savings begin to accumulate only when bundling frames longer than T_{RRC} which is typically set to a value around ten seconds.

Enabling DRX cuts the energy consumption to half without any bundling. The reason is that with a 30 fps framerate the DRX inactivity timer gets to expire in between subsequent frame transmissions and the UE can catch some sleep.

Since the DRX parameters can be set individually for each UE when establishing a connection with the eNodeB, we study next the impact of their values. We set both *on duration* and *DRX inactivity* timers to 1ms and short DRX timer to 100ms. It is beneficial to set the inactivity and on timers to small values in order to avoid the UE to spend excess time on active state. However. a too short inactivity timer may delay the delivery of TCP ACKs when the UE moves to DRX state very quickly after upstream data transmission, which may lead to spurious retransmissions and TCP falsely deducing network congestion.

We first disabled the short cycle and varied only the long cycle between 50 to 200 ms in steps of 25 ms. Figure 7 summarizes the results for 500kbps stream. In all the bar plots we present, the values shown are average power relative to the case of no bundling which is equal to 100. For completeness, we also include the case of uploading whole video in one shot (500s bundling). First thing we notice is that when bundling frames even just for one second, the power consumption is reduced by over 30% compared to streaming without bundling. Very long bundling period does not save significantly more energy than a few seconds long period. Longer DRX cycle leads to lower energy consumption but the net effect is rather small: only about 5% less energy consumed with 200ms long cycle compared to 50ms cycle. This small difference is caused by the very short value of the *on duration* parameter, which causes little energy to be spent per DRX cycle. Comparing Figure 7 to Figure 6 reveals that our analytical model suggests larger savings with bundling than the simulator does. We suspect that it is mainly caused by the simulator's more accurate power model which scales the tx power with sending rate whereas we assumed a constant tx power in Section 2.3.

Concerning the short DRX cycle, we found that the most important effect of enabling it was to avoid the spurious retransmissions as we described above. The impact of tuning that cycle was even smaller on the average power draw than in the case of the long cycle. The reason is that in between bundle transmissions the short cycle is active only for a relatively short time before the long cycle activates.

4.2 Impact of video bitrate

We next studied the impact of the video quality by varying the encoding rate. We used 50ms long DRX cycle and 20ms short cycle. Other parameters remained the same. Figure 8 shows the results when varying the video bitrate.

We note that the video bitrate has a large impact on the energy savings so that the higher the video quality, the less energy is saved through bundling. The reason is the following. When video bitrate increases, more data needs to be transmitted for the same bundling period. Since the uplink capacity remains the same, larger amount of data takes also longer to transmit, which leads to higher average power draw. Moreover, because streaming without bundling consumes always roughly the same amount of energy (constantly high power draw), the relative difference between the case of no bundling and bundling using a specific period gets smaller when the bitrate increases.

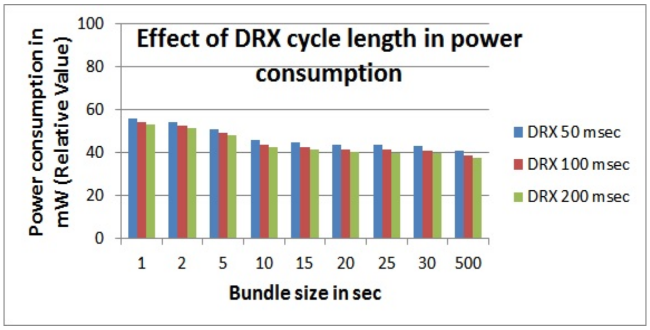

Figure 7: Results of tuning DRX long cycle

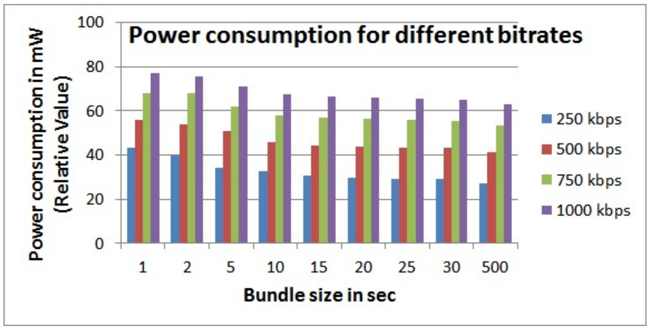

Figure 8: Results with different video bitrates

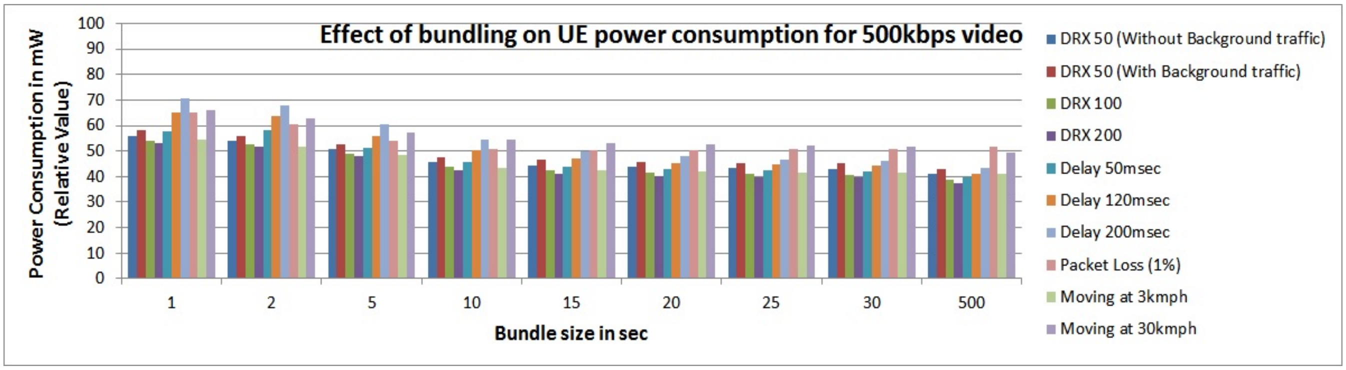

Figure 9: Comparison of all the scenarios

4.3 Impact of network conditions on energy savings

In the last set of simulations, we investigated the impact of RTT, mobility, packet loss, and background traffic on the energy savings. The results are summarized in Figure 9.

4.3.1 Round-trip time

We first added some delay into the baseline RTT which was about 40ms on the average and includes delay components from the radio access network, LTE transport network, and the Internet. Specifically, we increased the delay added by the Internet in Figure 1 which contributes by default only 4ms to the one way delay. We pinged a number of destinations to get realistic values for the Internet's part of the RTT: 5ms (within a country), 50ms (within EU), 120ms (Transatlantic), 200ms (to the Far East).

We observe that increasing delay does have a clear impact on the energy savings, especially when using a short bundling period. For example, with 1s bundling period, the energy savings compared to the case without bundling are 44% within a country (5ms RTT) and only 29% when transmitting a long distance (200 ms RTT). A longer RTT increases the bundle transmission time and leads to more energy spent because TCP only transmits new packets when previous ones have been acknowledged and also increases the congestion window based on received ACKs (see (2)).

4.3.2 Background traffic

Bundling effectively reduces the energy consumption only when the UE can transmit the bundle quickly at the end of each bundling period and sleep the rest of the time. Hence, competing cross traffic by other UEs on the radio access network reduces the uplink resources that can be allocated to a single UE. In order to understand how much such cross traffic reduces the energy savings achievable by bundling, we simulated scenarios with 700 UEs constantly uploading/downloading data and a single UE streaming using bundling over the uplink at the same time. The background UEs were created in such a manner that the aggregate background traffic load was constantly 2 Mbps.

As shown in Figure 9, there is a noticeable increase in energy consumption when cross traffic is present but the increase is not significant (overall 2% increase) at this load. We did not simulate scenarios where the network is under high load because operators try to avoid running their network in such regimes in any case.

4.3.3 Mobility

We used two UE speeds to evaluate the impact of UE mobility. Surprisingly, when the UE moves at 3kmph, bundling saves slightly more energy than in a static scenario. We looked at the reasons behind this phenomenon in detail and it turns out that it is caused by mobility providing the opportunity for the UE to move away from a bad to a better coverage area, which improves the power efficiency of bundle transmission. However, when the UE moves at a speed of 30kmph, there is notably less energy saved compared to a UE moving at a speed of 3kmph regardless of the bundling period. The increase is mainly caused by frequent handovers which add a signaling overhead and delay bundle transmission.

4.3.4 Packet loss

In case of packet loss, TCP retransmits the packet and reduces the transmission speed according to the congestion control algorithm used. Such an event increases the transmission time of a bundle and the energy consumption. In order to get an idea of the magnitude of the increase in energy consumption, we simulated a scenario with 1% packet loss in the Internet. The results suggest that the UE's energy consumption increases by 10% on average.

5. CONCLUSION

In this paper, we studied the energy saving potential of bundling video frames prior to transmission when streaming video from a LTE UE through the Internet. Our simulation results suggest that it is indeed a highly effective mechanism to save energy: 1s bundling can cut the energy consumption almost to half in the best cases. While certain AR applications that rely on instant feedback on streamed video cannot tolerate such added delay, many other applications and scenarios can find this tradeoff very useful. Video bitrate does have a major impact on the energy savings achievable and some of the network conditions related parameters, such as RTT, have an effect as well.

As future work, we would like to evaluate bundling in a real LTE network to uncover possible practical limitations. We are currently building an Android prototype. Adding audio or other traffic originating or destined to the same UE provides an additional challenge to bundling where the goal is to schedule the traffic in an energy efficient manner but at the same time respecting the possible timing constraints of some of the flows.

6. ACKNOWLEDGMENTS

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