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Energy Usage of UDP and DCCP over 802.11n

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***Abstract*—We show that the Datagram Congestion Control Protocol (DCCP) provides $\sim$10% – $\sim$40% greater energy efficiency than the User Datagram Protocol (UDP) in a wireless LAN (WLAN) client. Our empirical evaluation uses a testbed comprised of consumer components and opensource software to measure typical performance that can be expected by a user, rather than highly-tuned performance which most users will not be able to configure. We focus our measurements on a scenario using IEEE 802.11n at 5GHz as energy efficiency will be particularly important to mobile and wireless users. We consider overall performance as well as the energy efficiency of the protocol usage to give a rounded comparison of UDP and DCCP. Overall, we see there would be great benefit in many applications using DCCP instead of UDP.**

I. Introduction

Energy usage of computer systems and infrastructure is becoming increasingly important for a number of reasons:

- *Battery life*: Users wish to have better battery life from mobile devices and applications.
- *Energy costs*: Costs of energy are increasing, so reducing energy usage can reduce costs. This is important for the individual user, as well as for organisations concerned with system-wide OPEX.
- *Carbon footprint*: By improving energy efficiency, we can reduce the carbon footprint of users. This is a wider societal goal, and as ICT usage grows worldwide, there is a social responsibility to consider energy costs in new ICT components and systems.

While much focus has been on new techniques for energy savings and efficiencies in datacentres (e.g. [1]), client systems outnumber server systems and datacentres by several orders of magnitude. As consolidation of datacentres and application of mature datacentre techniques (e.g. virtualisation [2]), energy savings in the datacentre will start to be come marginal, yielding smaller returns on energy efficiency measures. However, by scale of numbers, even modest savings and efficiencies in energy usage at the client systems could yield significant impact when considering the worldwide population of users. Additionally, mobile data users are showing the largest growth [3]. So, we wish to examine protocols used for communication on client systems, especially for mobile users, with a view to improving application energy efficiency.

This paper reports on part of a larger body of work focussed on assessing and improving energy efficiency at the client side. Specifically, here we compare the use of a widely used transport-layer protocol, the User Datagram Protocol (UDP), with a more recent protocol, the Datagram Congestion Control Protocol (DCCP). Both offer datagram delivery, but DCCP allows congestion control to be applied across the packet flow, whereas UDP allows packets to be transmitted in an unconstrained manner.

A. Motivation and Approach

We explore the possibilities of improving client-side energy efficiency by changing the configuration of applications or other client-side software components that are amenable to application developers and application programming interfaces (APIs). If we can observe energy efficiency gains through such application-level adaptations, then they could be applied to a large base of legacy applications to achieve improved energy efficiency, even in the absence of newer, energy-efficient hardware [4]. If energy efficient hardware is present, any application-level adaptation can work in complement. Indeed, it should be possible to leverage different lower-level systems characteristics of legacy deployments for the benefit of application-level energy usage without impacting application-level performance [5].

Our approach is empirical, based on measurements of performance and energy usage of real systems. We use off-the-shelf equipment, opensource software, and consumer devices wherever possible. Our intentions are:

- To examine systems that are typical of normal consumer usage, so that our results are more likely to reflect real operation scenarios, rather than lab-specific, custom configurations.
- Make it possible to apply our methodology easily to other similar scenarios.
- Allow our results to be validated / reproduced easily.

Additionally, while it would be possible to examine the energy efficiency of individual components, we take the position that examining the system as a whole and the impact of energy usage of the client system as a whole allows the overall benefit to be assessed more readily.

B. Contribution and structure of this paper

Our contribution is to show the energy efficiency of DCCP in comparison to UDP for wireless usage on 802.11n at 5GHz. Our empirical evaluation gives clear evidence of the improvements that are possible. We cover a wide range of traffic loads and so provide a ‘performance envelope’ for our results, which gives the upper and lower bounds of the gains that would be possible. We also show the dramatic energy savings that are possible at scale when small efficiencies are implemented at the client side.

We first present some related work in Section II covering energy measurement, wireless LAN (WLAN) performance and protocol performance. We then present our methodology and metrics for our evaluation in Section III. In Section IV, we discuss our observations and provide analyses of the energy efficiencies that we actually as well as the potential that is made possible. We conclude with a summary and some pointers to future work in Section V and in SectionVI.

II. Related Work

Our own previous work in this area, using a similar methodology and testbed, established the use of the energy metric, E_A (see Section III-C) and the notion of the *energy envelope*, which gives the upper and lower bounds of the energy usage during the transmission of a flow [6]. We have also investigated the possibility of application adaptation within the scope of this energy envelope [4] to trade of performance against energy usage. Also the comparative effectiveness of the generic 802.11 power save mode (PSM) versus the application adaptation approach has been explored [7].

Halpern *et al* [8] provide an empirical study of the power consumption of 802.11n WLAN. They conclude that using larger packets and higher date rate in transmission is more energy efficient than using a smaller packet size and lower data rate. However, the authors draw this conclusion by measuring the energy consumption directly at the wireless NIC, whereas we consider the system as a whole.

Li *et al* [9] have examined the impact of the packet size to the energy consumption in heterogeneous wireless network environments. The study shows the importance of choosing the proper packet size in saving energy in a scenario composed of a body sensor network and WiFi network.

Previous studies have investigated the performance of the DCCP protocol in WLANs [10]–[12]. The authors provide an evaluation of the fairness of the 802.11g's hand-off mechanism using different transport layer protocols (TCP, UDP and DCCP). The study focuses only on the hand-off scenarios and considers the throughput as the only metric in the evaluation.

Navaratnam *et al* [12] have conducted a simulation based study on DCCP performance in wireless mesh networks. The study compares DCCP to UDP and TCP protocols in terms of the fairness and throughput smoothness. The study dose not consider application-specific performance or energy consumption.

Performance evaluations of DCCP also have attracted research interests in the field of wired networks, e.g. our own work [13], [14]. We have evaluated the performance of the DDCP CCID2 congestion control against the TCP NewReno, BIC and CUBIC. The study has been conducted by experimental 'out-of-the box' configurations using linux on an in-house testbed. However, these did not consider energy usage.

Wang *et al* [15] develop an application architecture of a VoIP application using DCCP. The authors implement this architecture on *Linphone*[1] 'an opensource IP phone'. However, this study does not provide an evaluation of the proposed architecture and does not consider energy usage. Meanwhile, RFC4828 [16] makes recommendations on how DCCP can be used for VoIP, but again does not consider energy usage.

III. Experiment Design and Metrics

The aim of our experiments was to study the impact of the DCCP and UDP transport protocols to the energy usage of WLAN clients. Our results provide mobile/computer application developers and the WLAN's solution providers with a guide to chose a suitable transport protocol and apply appropriate tuning to save more energy on a user's devices while delivering the same quality to them.

In our experiments, we have used 'out-of-box' configurations, as we believe most users do not have the expertise or inclination to fine- tune their equipment. We used only standard, un-tuned WLAN radio- channel configurations and system parameters. Many WLAN NIC drivers permit various controls of the NIC hardware, but this is not easily accessible or comprehensible for adjustment and tuning by most users. We used the 5GHz band for our testbed as we have exclusive usage of it within our environment, and so our experiments were free from interference from other WLAn deployments. Additionally, the 5GHz band is becoming more widely used as 2.4Ghz becomes more crowded, and the newest variant of 802.11 – 802.11ac – currently uses 5GHz only.

A. Overview

For the two transport protocol scenarios, we generated packet flows of various bit-rates and packet sizes, and measured power usage during the packet transmission. As shown in Fig. 1, the testbed consisted of a single client host, a host running a wireless access-point (AP) and experimental control units (only one shown in Fig. 1) for monitoring the WLAN environment, providing storage for measurement data, *ntp* [2] services and system configuration. The WLAN hosts were set up in a teaching lab in the University of St Andrews with a distance of $\sim 24\ \pm 0.5$ m between between the antennae.

We used 40MHz channels, with 2 antennae at both client and server/AP. This is the minimum configuration required to support 802.11/5GHz, and is also the most common configuration as it is the least costly to implement, and also the easiest to implement in smaller devices, where device sizes and geometry might inhibit additional antennas.

The DCCP extension of the *iperf* tool [3] was used as a packet generator and for conducting the performance measurement of the experiments. The CCID3 [17] has been used in the experiments, which uses TCP-friendly rate control, which is appropriate for real-time applications. A wrapper script executed *iperf* and extracted throughput and loss for individual UDP/DCCP flows using the *iperf server report*. Power consumption was measured at the client and the AP using a commercial power meter.

[1] http://www.linphone.org/

[2] http://www.ntp.org/

[3] http://www.erg.abdn.ac.uk/ gerrit/dccp/apps/

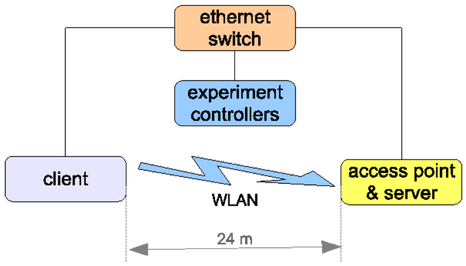


Fig. 1. Schematic of testbed showing physical connectivity. All experiments used 802.11n at 5GHz with 40MHz channels. The experiment controller uses Ethernet for control messages and shared file-system access to avoid control traffic interfering with test traffic on the WLAN. The separation between the antennas of the client and access point/server was $\sim 24 \pm 0.5$ m. Data packets generated by *iperf* were transferred across the WLAN.

B. Workloads: packet flow configuration

Our intention was to provide a detailed coverage of the performance landscape for 802.11 and energy usage. So, we configured the UDP and DCCP flows across a range of bit rates, with small and large packets. We chose an upper limit of 30Mbps data rate for a single flow, as there are very few applications that would need to run at such high rates for single flows: even streaming of HD video (using consumer encodings such as H.264 or H.265, rather than 'raw' streams) requires less than 10Mbps[4]. Currently, the UDP protocol is widely deployed to support multimedia applications such as Voice and Video over IP (VoIP and ViIP) for real-time, interactive services. This study shows the benefits possible if DCCP is used to replace UDP in supporting such applications in terms of energy consumption.

TABLE I
GENERIC UDP/DCCP WORKLOAD.

Packet size in offered load	64; 1440 bytes
Offered load's bit rate	0.031; 0.049; 0.25; 0.5; 1; 2; 3; 4; 5; 6; 7; 8; 9; 10;12; 14; 12; 14; 16; 18; 18; 20; 22; 24; 26; 28; 30 Mbps

Each packet size was combined with each bit-rate (26 combinations); 40 flows measured with each combination executed for each of UDP and DCCP (1040 flows for each); each flow had a duration of 2 minutes, giving a total of ~69 hours of measurements.

Table I shows the data rates and packet sizes used in the experiments. The 64 byte packet is the smallest size for which we have observed that *iperf* is able to generate server reports, and very few applications will have packets smaller than this. The 1440 byte packet is chosen as that is maximum packet size allowed for each active DCCP session (MTU size) [18, Section 14.1] in *iperf*.

Additionally, in order to examine the performance and the energy usage of multimedia applications, we emulate Skype (VoIP) and YouTube (ViIP) flows. Traffic emulating a Skype (VoIP) flow was based on previous studies [19], [20], as was traffic emulating a YouTube (ViIP) flow [21], [22]. We acknowledge that YouTube is not real-time, but for the sake of using a well-known video encoding, and to permit comparison with our previous work [4], [6], [7], we use the YouTube flow construction. The relevant parameters are given in Table II. We emulated 5 sequential flows for each application for both UDP and DCCP protocols.

TABLE II
APPLICATION WORKLOAD EMULATION.

Skype	300 byte packets, 65 Kbps
YouTube	1431 byte packets, 639 Kbps

5 measurements with each flow (10 flows); flow duration of 4 minutes; $\times 2$ gives $\sim$1.5 hours of measurements. The emulated workloads are based on [19]–[22], as well as on measurements in [6].

C. Metrics

We used some directly observed measurements and also some derived metrics in order to evaluate performance and energy usage. The following metrics are consider in our study:

- *Power consumption:* We measured power consumption on the client side at 30 second intervals which is then used to find the energy usage of the client. The Effective Application-specific energy-usage E_A has been used [6] as shown in the following:

$$E_A = \frac{\text{mean power used during transmission of flow}}{\text{mean throughput of flow}}$$

  E_A has units Joules/Mega-bit (J/Mb):

$$\frac{\text{power in Watts}}{\text{throughput in Mbps}} = \frac{J/s}{Mb/s} = J/Mb$$

  and the lower the value of E_A, the better in terms of energy usage. To generate values for E_A, for each individual flow, we use the following measurements:

$$E_A = \frac{P_A - P_I}{T_A} \tag{1}$$

  P_A Mean power consumption measured during the transmission of flow [Watts].
  P_I Mean power consumption measured for an idling node [Watts].
  T_A Mean throughput measured (using *iperf*) during flow transmission [Mbps].
- *Performance:* Throughput and loss, as recorded by *iperf*'s server reports, on the client for each flow.
- *WLAN rates:* The Modulation and Coding Schemes (MCS) used during the experiments, as reported by the WLAN NIC driver, giving the channel rate for the WLAN RF channel.

Table III summarises the observables measured during the experiments and the metrics derived from the observations.

D. Equipment

Our testbed was equipped with an identical machines. The hardware specifications of the client, server and the observer were: a Shuttle X (*XPC Barebone SS56G* [5]) with an Intel®

[4]4K video will be interesting for the future!

[5]http://www.shuttle.eu/_archive/old/es/www.shuttle.eu/html/index-416.html

TABLE III
OBSERVABLES AND DERIVED METRICS FOR THE EXPERIMENTS

Observable / metric	Units	Comment
Power	Watts	power meter at the client
Energy efficiency E_A	J/Mb	As defined in [6]
Performance	throughput - Mbps loss - %	*iperf* server reports
WLAN rate (MCS)	bit rate - Mbps	from *iwconfig*

Pentium® 4 CPU 3.00GHz, 1GB RAM, 112GB HD. All machines used the same wireless LAN NIC hardware [6] based on the popular Atheros [7] chipset. Compared with today's modern desktop specifications, this would be considered modest at best, but the parameters and performance are similar to today's high-end mobile devices, such as smartphones and tablets. Our powermeter is by a company called i-Sockets[8].

Ubuntu 10.04 was used on each machine, a minimal server distribution, with the default kernel 2.6.32-24-generic-pae, and the WLAN modules compat-wireless-2011-05-02. For running the AP we have used the *hostapd* [9] package with default parameters. Ubuntu 10.04 contains *hostapd* version 0.6.9. All nodes in the testbed ran in an isolated network. The system clocks of all the nodes where synchronised (using NTP [23]) before each individual experimental run. The linux utility *iwconfig*[10] was used to record the MCS and so the bit rate used on the RF channel.

IV. RESULTS AND DISCUSSION

Our analyses are comparative between UDP and DCCP protocols and we are not concerned with *absolute* performance.

We first consider the energy usage of UDP and DCCP and then put this into context by considering the throughput and loss observed and what this could mean for VoIP and ViIP. Figure 2 shows the overall results. The key finding is: *DCCP is more energy efficient compared to UDP across that whole range of workloads*. This is discussed in Section IV-A. Our results effectively provide an *energy envelope*, and upper and lower bound for what energy efficiencies might be possible.

We expand on energy usage by considering flow-level performance in terms of throughput and loss. The throughput results are given in Figure 3 and the loss results are given in Figure 4. The key finding is: *for small packets, DCCP has better loss and throughput than UDP; whilst for large packets, DCCP and UDP have similar loss but DCCP has marginally lower throughput*. This is discussed in Section IV-B.

We put these results into context by considering multimedia streams, VoIP and ViIP, using traffic analyses by other researchers for Skype (VoIP) [19], [20] and YouTube (ViIP) [21], [22]. The key finding is: *based on our experiments, we believe that significant client-side energy savings can be made if DCCP is used to replace UDP for VoIP and ViIP*. This is discussed in Section IV-C and Section IV-D.

Finally, in Section IV-E we consider briefly some background related to our experimental work by considering the impact of the lower-level (WLAN) configuration and how this might impact our study.

In Figures 2, 3 and 4, we plot the mean point of the runs, and plot standard error bars (95% confidence), but in the majority of the experiments, only very small error bars were calculated, so they may not always be easily visible even though they have been plotted.

A. Energy Efficiency

Figure 2 shows the energy usage of the UDP and DCCP protocols of different packet size flows and under different traffic loads. For both packet sizes – from Figure 2a (64B packets) and Figure 2b (1440B packets) – we see that DCCP has better energy efficiency than the UDP protocol across the entire range of workloads.

To better show the difference between DCCP and UDP, in Figure 2c we show ΔE_A, which is defined simply as the percentage value of:

$$\frac{(E_A \text{ for UDP}) - (E_A \text{ for DCCP})}{(E_A \text{ for UDP})}$$

at the corresponding measurement points. So, positive values show where DCCP is more energy efficient. For small packets, DCCP is $\sim$10% – $\sim$40% more efficient than UDP. For large packets, DCCP is $\sim$10 – $\sim$30% more efficient than UDP.

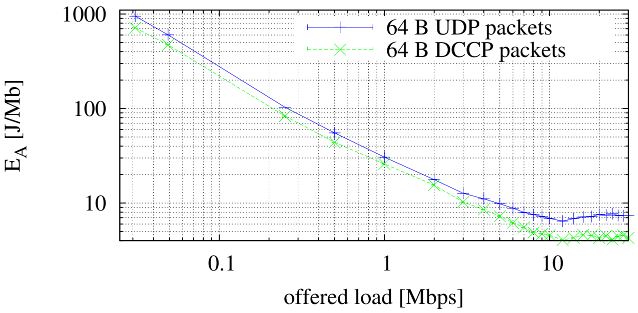
If we consider the graph for small packets in Figure 2c, while the trend is that the value of E_A increases as the load increases, we do see an initial drop up to our measurement at 2Mbps. Part of the explanation for this is the relative overhead of DCCP compared to UDP. Initially, with small packets sizes the computational overhead of DCCP (e.g. the CCID algorithm and buffer management) and the relative packet overhead drive the E_A value lower as the data rate increases. However, this effect is eventually overcome by the more significant impact of the increased loss on the overall throughput of UDP - the loss can be seen in Figure 4a, which rises dramatically at 2Mbps. The impact of loss and throughput is discussed further in Section IV-B.

This general trade-off between DCCP overhead versus overall performance is more easily visible for large packets. Unlike small packets, we see in Figure 4b, that the loss for UDP and DCCP with large packets is similar and very low. So, when we consider the difference in the E_A value in Figure 2c, we see that the trend for the line is that as the load increase, the ΔE_A is reduced, as first happens with small packets below 2Mbps. However, as the load increases, the comparative overhead for DCCP will increase, as, overall, DCCP has to perform more computations per packet than UDP.

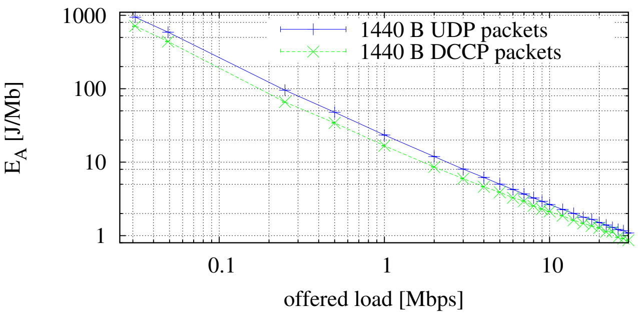
The small packet and large packet lines for each protocol give effectively, and *energy envelope*, which gives the upper and lower bounds of performance with respect to E_A values

[6] http://www.compex.com.sg/Datasheets/WLM200NX_DSv3.2.9.pdf
[7] http://www.atheros.com
[8] http://www.i-sockets.com/, we have also previously used the Current Cost CC128 power meter successfully.
[9] http://hostap.epitest.fi/hostapd/
[10] http://www.linuxcommand.org/man_pages/iwconfig8.html

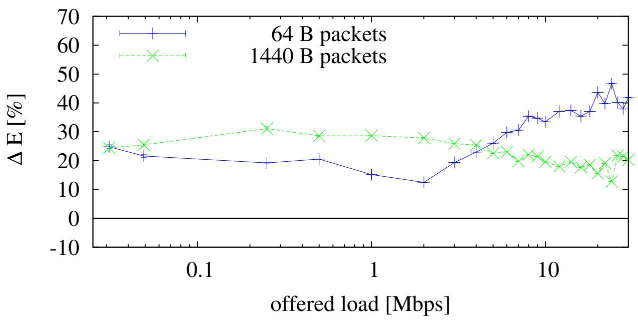
for the protocol. The exact E_A values could change due to differences in hardware and software in another equipment configuration, but the trends shown will remain similar.



(a) E_A for 64B packets



(b) E_A for 1440B packets



(c) Difference in E_A between DCCP and UDP. Horizontal zero line is a visual aid. Positive values indicate where DCCP has better energy efficiency.

Fig. 2. Application-specific energy usage, E_A, for DCCP and UDP.

B. Performance

In the discussion above, it is clear that flow performance has an impact on energy usage. Figure 3 shows the throughput for experiments and Figure 4 shows the loss. We show again separate graphs for small packets (throughput in Figure 3a and loss in Figure 4a) and large packets (throughput in Figure 3b and loss in Figure 4b).

It is clear that for smaller packets, DCCP has much better throughput than UDP, by as much as $\sim$80% at the higher load rates. We also see that at $\sim$2Mbps load and below, there is little difference between the two with large or small packets, and only a small difference of $\sim$10% up to 4Mbps load. The throughput for small packets for UDP levels out at $\sim$6Mbps when the load is 12Mbps and higher. For DCCP, with small packets, there is a similar plateau starting at 12Mbps load, but the throughput reached is $\sim$12Mbps, twice that of UDP.

With large packet sizes, we see that UDP has marginally better throughput, due to the lower packet overhead (smaller transport headers) - this is best seen in Figure 3c, which shows the difference between DCCP and UDP, as the percentage value of:

$$\frac{(\text{DCCP throughput}) - (\text{UDP throughput})}{\text{UDP throughput}}$$

For loss, as shown in Figure 4, the picture is much simpler. Below 2Mbps load, there is little difference in loss. Above 2Mbps load, only for small packets, the loss increases dramatically as load increases, levelling off at $\sim$70% when the load gets to 20Mbps and greater. Such high loss is not unusual and has been observed and analysed by others, e.g. Pelechrinis *et al* report high loss at high rates for 802.11n 5GHz [24].

However, the loss has a significant impact on the E_A value. The throughput takes into account all transmissions, but only counts successful deliveries (sometimes, this is referred to as 'goodput'). DCCP's better loss characteristics help give it better E_A values at higher rates with small packets. So, loss counts as wasted transmissions and wasted energy.

Additionally, as DCCP can control loss on and end-to-end basis, there are potential benefits for energy savings in the infrastructure also. Reducing congestion in the network along the end-to-end path reduces loss, reduces wasted transmissions (and re-transmission for those applications that use re-transmissions) and so will result in further energy savings. We have no assessed this in our current evaluation, of course.

C. Real-time voice and video

Table IV shows the E_A values for from traffic flows generated according to the description of Section III-B and Table II. The emulated traffic is for Skype traffic representing VoIP and the YouTube traffic representing ViIP, with the caveat already discussed in Section III-B that YouTube in actual use is not real-time.

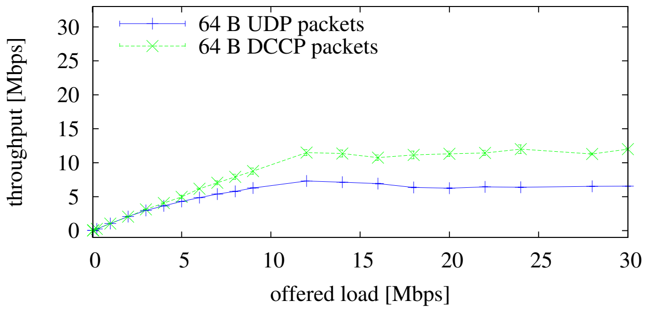
The table shows clearly the potential for energy savings by using DCCP instead of UDP. Our work takes the position that the client-side energy considerations could have significant impact, even with small savings per-client savings, due to the large number of client systems.

TABLE IV
ENERGY EFFICIENCY, E_A (J/MB) FOR VOIP AND VIIP EMULATIONS

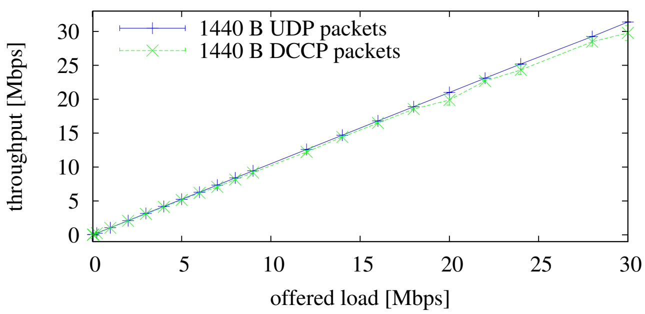
	UDP	DCCP	difference
Skype	454	334	120 (26%)
YouTube	45	33	12 (26%)

The final column shows the difference with respect to UDP. These are for 4-minute flows as described in Table II.

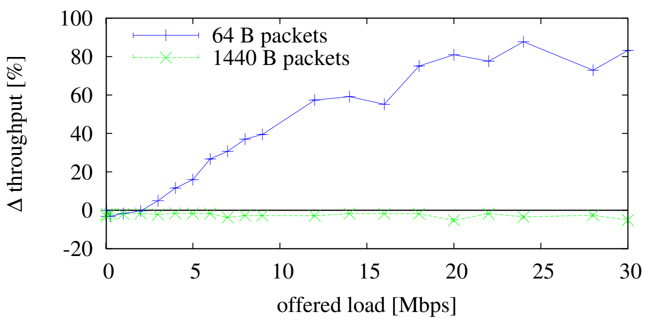
Another issue to consider here is that we have considered only the packet level and systems level issues that we can



(a) Throughput for 64B packets.

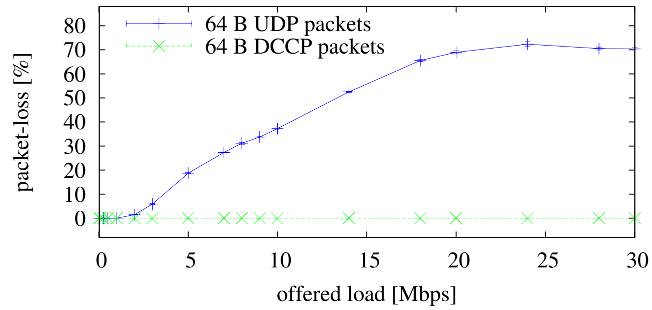


(b) Throughput for 1440B packets.

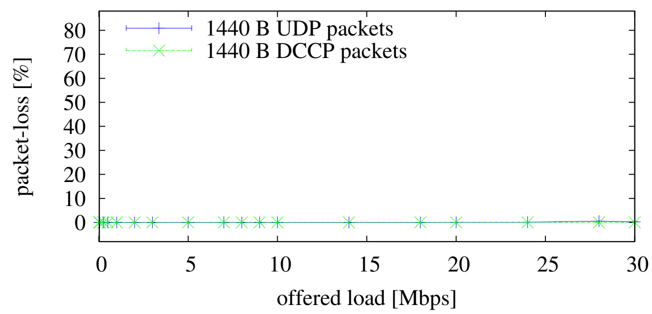


(c) Difference in throughput between DCCP and UDP. Horizontal zero line is a visual aid. Positive values indicate where DCCP has better throughput.

Fig. 3. Throughput for UDP and DCCP.



(a) Loss for 64B packets.



(b) Loss for 1440B packets.

Fig. 4. Loss for UDP and DCCP.

measure objectively, and are aligned with more traditional measurements of system and network Quality of Service (QoS). For an overall assessment on the impact of the use of DCCP in place of UDP at the application level, more subjective tests, for example with user trials, would need to be performed to assess Quality of Experience (QoE). Such assessments would be application-specific, whereas we have shown a general result which would need to be tuned for use within a particular context.

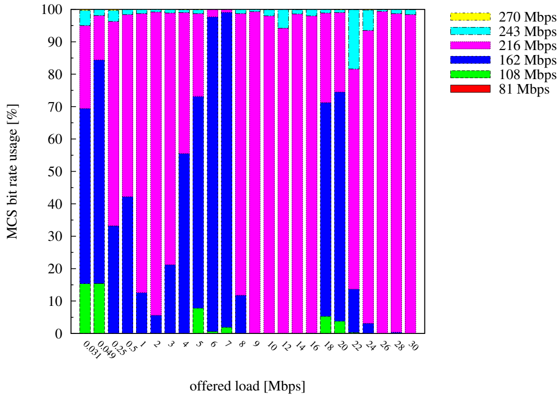
D. Energy savings

According to a recent report from TeleGeography[11], Skype-to-Skype voice and video traffic was estimated at 167 billion minutes in the year 2012. Using our data in Table II and IV, we can evaluate an energy saving with DCCP.

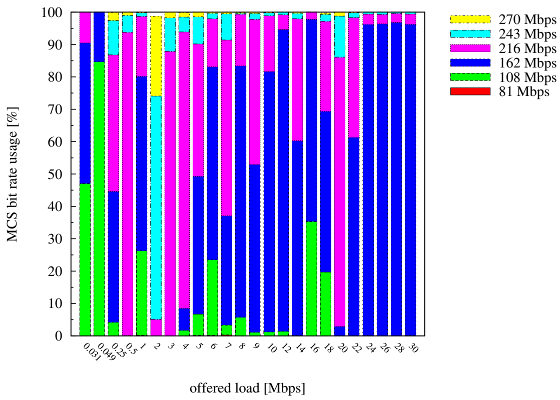
As an exercise, let us assume that all these minutes are for VoIP at 65Kbps (some of these minutes will be video but this gives us an upper bound), the total volume of traffic is 6.513×10^{11}Mb. If this is evenly distributed across the year, that is a constant 20,652Mb/s for every second of the year. The VoIP saving with DCCP is 120J/Mb for all clients, so the total energy saving is 7.815×10^{13}J or 78.15TJ. Another way of looking at this is that 20,652Mbps is 2,478.24KW of saved power. Over the year, this is 21,709,382 KWh. According to a report from the UK Government [25], the mean annual household electricity usage in the UK is 4,226KWh. So, the energy saving with DCCP for Skype would be enough electricity for 5137 homes in the UK for a year.

Of course, this evaluation is based on our measurements from a single, low-end desktop client system. Some desktop clients will consume far more energy and will have greater E_A values. Some client systems will be more energy efficient (e.g. mobile devices such as smartphones) and so will again have different E_A values. Also, different software and hardware will have different impact on energy usage, e.g. video codecs, display technologies, etc. However, the trends for E_A and the energy envelope will be similar due to construction and transmission of packets being similar for systems.

[11]http://goo.gl/KgCTE2 *The Bell Tolls for Telcos?*, Feb 2013

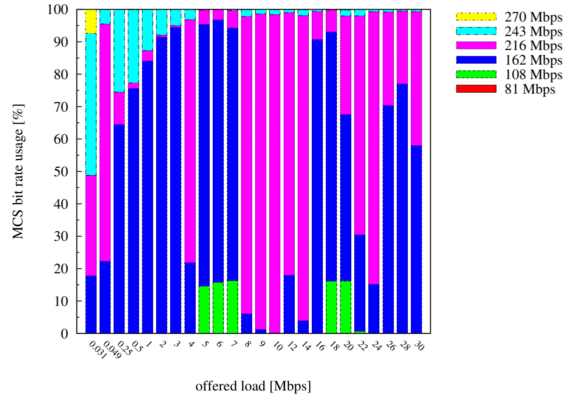


(a) MCS rates for UDP.

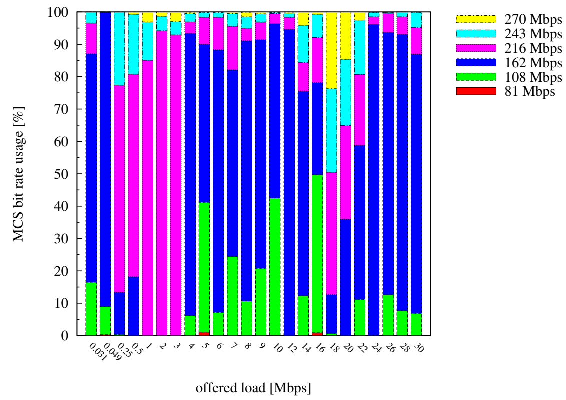


(b) MCS rates for DCCP.

Fig. 5. MCS bit rates for UDP and DCCP, 64B packets.



(a) MCS rates for UDP.



(b) MCS rates for DCCP.

Fig. 6. MCS bit rates for UDP and DCCP, 1440B packets.

E. WLAN transmission rate

This subsection shows the different bit rates selected by the driver, according to the Modulation and Coding Scheme (MCS) mappings in 802.11n. The main feature to observe here is one of a additional experimental configuration check on our results. We see in Figures 5 and 6 that the bit rate at the RF layer was always well above the offered load, with the minimum being 81Mbps for a very small fraction of time (hardly visible in Figures 5 and 6), and was mostly at 216Mbps or 162Mbps (recall that our highest offered load was 30Mbps). So, in our experiments, the WLAN RF transmission was never a bottleneck.

The bit rates, based on MCS, were chosen in our dynamically by the driver software. The MCS selection is a function of the received signal strength indication (RSSI) seen at the receiver. The RSSI can be effected by interference including RF multipath effects. This is more likely to impact higher loads, e.g. above $\sim$80Mbps in our case, but will vary for different uses, depending on how RSSI is impacted in the specific deployment scenario.

This could be an important factor for higher rate operation, as even with newer 802.11 variants, the higher data rates come from selection of a MCS that can yield better channel utilisation. Faster transmission speeds should reduce the transmission times for packets - NICs spend less time transmitting – and so could yield benefits for energy usage. However, we have not examined this feature explicitly in this study, and we leave this for future work.

V. Conclusion

From our empirical evaluation of the energy usage of 802.11n at 5GHz with UDP and DCCP, we find that DCCP offers energy savings with datagram-based traffic. DCCP may be $\sim$10% – $\sim$40% more efficient in terms of energy for the same traffic profiles as for UDP. Our experiments provide an *energy envelope* that gives the upper and lower bounds of what is possible with respect to energy efficiency.

We also assess the network level flow performance by considering other performance issues such as throughput and loss for the flows. We find that DCCP performs better in terms of throughput and loss also, compared to UDP.

We also place our results in context by considering emulations of Skype VoIP traffic and YouTube ViIP traffic. We find that VoIP traffic would certainly benefit from an energy efficiency point of view if DCCP was used in place of UDP, with our evaluation showing possible energy efficiencies of $\sim$50% for our emulated Skype traffic. However, this is subject to more rigorous assessment, such as QoE evaluations. As part of this context setting, we show the dramatic energy savings that might be possible if the scale of numbers in client systems was considered for such modifications from UDP to DCCP for VoIP traffic.

VI. Future Work

Our work is part of an ongoing view that software systems, client systems and users have at least as important roles to play in energy efficiency for ICT systems as do the hardware systems, datacentres and virtualised platforms which are a major focus of industry and researchers today.

We intend to perform a more in-depth analyses of our scenario, including looking at the problems of energy efficiency when multiple client systems compete for resources in the WLAN environment.

We also expect that similar energy efficiency could be made by examining carefully the system components, e.g. we are currently considering the energy profile of various video codecs.

Our aim, eventually, is to enable adaptive applications and systems, which can trade-off measured QoS as well as the users expectations and requirements on QoE to produce performance that is tuned for a task, but is energy efficient.

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