An Energy-aware Multipath-TCP-based Content Delivery Scheme in Heterogeneous Wireless Networks

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***Abstract*—IETF-proposed Multipath TCP (MPTCP) extends the standard TCP and allows data streams to be delivered across multiple simultaneous connections and consequently paths. The multipath capability of MPTCP provides increased bandwidth for applications in comparison with the classic single-path TCP, which makes it highly attractive for the current consumer mobile devices that support more than one radio interfaces (e.g. 3G, WiFi, Bluetooth, etc.). However, MPTCP does not consider energy consumption aspects which are highly important for these devices. This paper proposes eMTCP, a novel energy-aware MPTCP-based content delivery scheme which balances support for increased throughput with energy consumption awareness. eMTCP is located at upper transport layer in mobile devices and requires no additional modifications of the MPTCP-enabled server. eMTCP increases the energy efficiency of mobile devices by offloading traffic from the more energy-consuming interfaces to others. Simulation-based experiments employing an eMTCP model which sends data streams via the 3GPP Long Term Evolution (LTE) and IEEE 802.11 (WiFi) interfaces show an increase of up to 14% in energy efficiency when using eMTCP in comparison with MPTCP and of up to 66% in terms of quality in comparison with single-path TCP.**

***Index Terms*—energy consumption, WiFi, Long Term Evolution (LTE), Multipath TCP, traffic offloading**

I. Introduction

WIRELESS networks and the associated technologies are widespread in modern human society. One of the most commonly used wireless networks is the broadband wireless local area network supported by the IEEE 802.11 protocol family (WiFi) [1], which provides good communication quality for users in small coverage areas such as homes or offices at low deployment costs. Cellular networks, on the other hand, are the most important communication technologies which provide large-area signal coverage but have lower bandwidth and higher deployment and maintenance costs. 3GPP [2] Long Term Evolution (LTE) [3] is a state-of-the-art technology which significantly improves the bandwidth in cellular networks.

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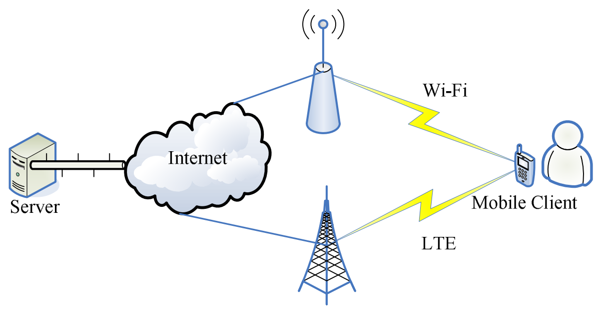

Fig.1. Multipath communication using LTE and WiFi

Data transmission between wireless mobile devices via WiFi or LTE networks is handled by transport layer protocols and the most widely-used is TCP. Investigations in [4] show that more than 95% of total traffic over the Internet is delivered using TCP, including various types of application services such as email, web browsing and social networking. Lately TCP is also used for applications such as video streaming and voice over IP which have higher requirements for both bitrate and delay. However, there are severe limitations in the performance of TCP usage over wireless networks for these applications and Multipath TCP (MPTCP) [5] [6] was introduced to solve this problem. In MPTCP, data transmission is performed through multiple channel paths simultaneously instead of using a single path as in the classic TCP. In general, throughput obtained by MPTCP connection over multiple paths is much higher than a single TCP connection.

One of the concerns when using MPTCP for wireless data transmissions is the energy consumption of the battery-powered mobile devices due to their limited power resources. For example, suppose that both WiFi and LTE access are available for a smartphone waiting for remote data transmission, as shown in Fig.1. When single-path TCP is used, one interface is active only. When MPTCP is used, the total energy consumption increases since both LTE and WiFi interfaces are active, which severely reduces the battery life.

This paper presents a novel **energy-aware MPTCP-based content delivery scheme** (eMTCP), deployed at the upper transport layer of mobile devices. eMTCP increases the throughput of applications with high bitrate and delay sensitivity data transfer requirements in comparison with single-path TCP solutions and saves energy in comparison with MPTCP. eMTCP achieves higher energy efficiency by monitoring the channel status of each of the transmission paths and offloading traffic from the most energy-consuming interface to the other interfaces. Additionally, this paper investigates how different traffic offload levels affect the transmission performance in terms of energy consumption and throughput in the context of eMTCP data transfer via LTE and WiFi interfaces. eMTCP was modeled and tested via Network Simulator 3 (NS-3) simulations in comparison with MPTCP and TCP. The results show how eMTCP best balances energy saving and delivery performance, outperforming MPTCP in terms of energy saving and TCP in terms of throughput and estimated user-perceived quality.

The remainder of this paper is organized as follows. Section II presents related works on multipath and multihoming communications and MPTCP-based optimization. Section III and IV describe the architecture, principle and detailed functionality of eMTCP. Section V describes the simulation-based test bed settings and presents the relevant test results. The last section summarizes our work and presents future work plans.

II. Related Works

Recently, many solutions have been proposed for high bitrate, delay sensitive and/or energy-aware content delivery, including [7-11]. Some of these solutions involving multipath and multihoming communications [12] and MPTCP-based optimization are discussed next.

A. Multipath and Multihoming Communications Approaches

Strict requirements in terms of throughput, reliability and timeliness are increasingly common in current data transfer applications. One way to address such requirements is the usage of multipath and multihoming technologies.

The Stream Control Transport Protocol (SCTP) [13] provides concurrent and reliable multipath data transfer via data duplication detection and retransmission. Each SCTP host selects a primary IP address from a list of IP addresses it maintains. A SCTP association is established consisting of one primary connection and several secondary connections. When the primary connection fails, switchover is triggered to a secondary connection. However, SCTP has not been widely deployed as: 1) it needs support from the application layer, which incurs increased implementation costs; 2) in many real-life cases the SCTP packets might be blocked by middle boxes (i.e. network address translator) or firewalls. In contrast with SCTP, MPTCP is a transport layer protocol which does not need application modifications. Additionally, MPTCP uses traditional TCP packets towards which the majority of existing middle boxes and firewalls are friendly.

Shim6 [14] proposed by IETF offers a multihoming solution for IPv6. Typically, a Shim6 host maintains a list of IPv6 addresses, each of which is given by its service provider. Shim6 utilizes REAchability Protocol (REAP) [15] to deal with failures. Whenever failures are detected, REAP recommends an alternative pair of IPv6 addresses that enable the two hosts to communicate with each other. Shim6 is attractive when a best path is to be selected for packet delivery. For instance, when a communication path is established between two Shim6 hosts, packets can be delivered through that path with low delay by pairing appropriate addresses. However, Shim6 has not been widely deployed in real-life cases either.

B. MPTCP-based Optimization Approaches

Lately the research effort on MPTCP-related traffic optimization is growing fast. In [16], an energy-aware congestion control algorithm for MPTCP called ecMTCP is proposed, which reduces energy by offloading traffic from one link with higher energy cost to the other one with lower cost. The amount of increase in the congestion window size in ecMTCP is inversely proportional to the energy cost of each link. The disadvantage of ecMTCP is that it requires considerable modifications of the original MPTCP. Moreover, ecMTCP needs implementation support both at server side and client side, which makes its deployment less attractive. NC-MPTCP [17] includes a packet scheduling algorithm and a redundancy estimation algorithm to allocate data among different MPTCP sub-flows in order to optimize the overall goodput. Simulations-based experiments show that NC-MPTCP achieves higher goodput compared to MPTCP in the presence of different sub-flow qualities. However in the worst case, the performance of NC-MPTCP is almost the same as that of single-path TCP. The work in [18] proves the feasibility of using MPTCP for mobile traffic handover in WiFi/3G networks and analyzes the energy consumption and handover performance of MPTCP in various operational modes. It also proposes a simple solution for the influence of MPTCP control signal loss on handover performance.

Unfortunately, none of these research works considers both the balance between energy consumption and increased throughput and development friendliness as eMTCP does.

III. eMTCP Architecture and Principle

The block architecture of the proposed eMTCP scheme is illustrated in Fig.2, considering two wireless network technologies: LTE and WiFi. The architecture involves the following two components deployed at the upper transport layer:

1) *Sub-flow Interface State Detector (SISD)*: continuously observes the channel state of the WiFi and LTE interfaces. These states can be:
   - *Receiving (RX)*: the interface receives data.
   - *Idle*: the interface waits for incoming data (no data is transferred).
2) *Offload Controller*: prepares for offloading some traffic from the LTE sub-flow to the WiFi sub-flow. The offload amount is decided according to the current congestion window size of the LTE sub-flow and the feedback of interface channel state change from SISD.

Traffic offloading events in eMTCP are also related to the status of the MPTCP congestion control mechanism which adaptively makes the decision which sub-flow to use to deliver

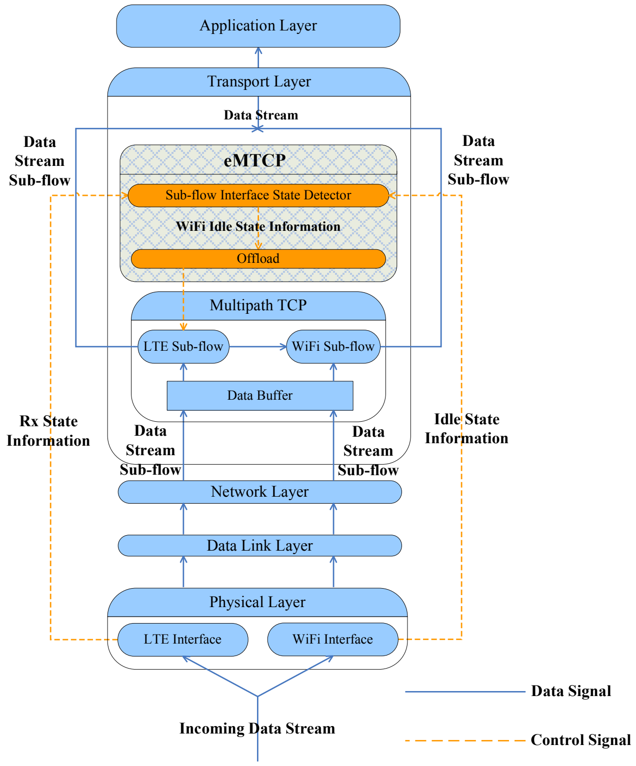

Fig.2. Architecture of eMTCP deployed in mobile devices

data stream according to the alteration of the congestion window size. For example, suppose there are two sub-flows in MPTCP: A and B. If sub-flow A has its congestion window size 0 while the congestion window size of sub-flow B is larger than 0, the congestion control mechanism decides to stop delivering data traffic to sub-flow A and switch to sub-flow B.

SISD keeps track of transmission channel state information for both WiFi and LTE. Once it senses the *RX* state at the LTE interface and *idle* state at the WiFi interface, indicating that the data stream is going through the former, it informs the offload controller that the WiFi interface is available to be used by sending messages containing the corresponding hint information of the current channel state. In this way the energy consumption of the mobile device is reduced since more data is carried via the WiFi interface which consumes less energy than the LTE interface, while also avoiding any congestion in the overall traffic.

The detailed description of eMTCP is provided next.

IV. eMTCP Algorithm Description

This section describes the eMTCP algorithm, which uses the following parameters:

1) S_B – size of remaining data in the data buffer at the transport layer.
2) S_{WiFiW} – congestion window size of the WiFi sub-flow.
3) S_{LTEW} –congestion window size of the LTE sub-flow.
4) S – size of data obtained from the TCP receive buffer.
5) ST_{WiFi} – current channel state of the WiFi interface.
6) T_{RX} – instant time stamp when the LTE interface is about to receive data.

TABLE I
Algorithm Pseudo Code for eMTCP

```
S = 0;
while (1)
{
    if (T_RX is detected in LTE sub-flow)
    {
        if (ST_WiFi == idle)
        {
            if (S_WiFiW > 0)
            {
                S = min(S_B, S_WiFiW);
                Offload S amount of data to WiFi sub-flow;
            }
            else
            {
                if (S_LTEW > 0)
                {
                    S = min(S_B, S_LTEW);
                    Send S amount of data via LTE sub-flow;
                }
                else
                {
                    Perform congestion control;
                }
            }
        }
    }
}
```

Using the parameters listed above, the data traffic offload process works in three steps as follows:

1) When T_{RX} is detected by *SISD*, it checks whether the WiFi interface is in *idle* state. If so, *SISD* confirms the current availability of the WiFi interface.
2) When the congestion of the WiFi sub-flow is detected (the congestion window size is 0), the algorithm checks if the LTE sub-flow is in congestion as well. If so, the current data reception will be abandoned and the congestion control mechanism will be triggered. If not, it takes the queued data from the TCP receive buffer out to the LTE sub-flow.
3) In step 2), when data traffic is not congested in the WiFi sub-flow, the queued data in the TCP receive buffer is offloaded from the LTE sub-flow to the WiFi sub-flow.

By using eMTCP, multipath TCP-based delivery can be achieved with higher energy efficiency since the WiFi interface is utilized when possible instead of the LTE interface which is responsible for larger energy consumption.

The pseudo code of eMTCP is presented in Table I.

V. Simulation-Based Testing and Result Analysis

This section presents the detailed settings for the simulation-based testing. Modeling and simulation were performed using Network Simulator 3 (NS-3) version 15 [19]. Data transmission performance during simulation is measured in terms of the ***remaining energy*** after certain time period (which represents the energy consumption), ***average throughput, energy efficiency*** (ratio between throughput and energy consumption), ***estimated battery lifespan*** and ***user perceived quality***.

A. Simulation Test-bed Setup

The network topology used in simulation is presented in Fig. 3. It involves twelve wireless nodes: one used as data source

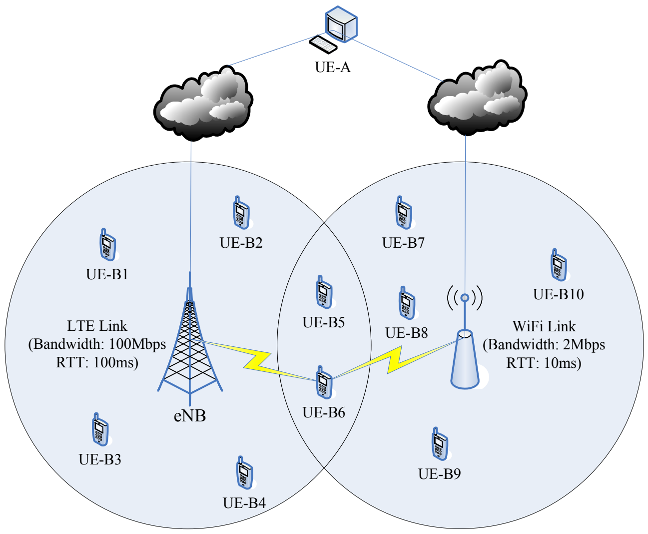

Fig.3. Network topology used in eMTCP simulations

(referred to as UE-A), another ten used as data sinks (referred to as UE-B1, UE-B2...and UE-B10, representing ten mobile devices) and one used as eNB node in the LTE network. UE-B1, B2, B3 and B4 are within the signal coverage of the eNB node (the base station in LTE structure) only, while UE-B7, B8, B9 and B10 are within the signal coverage of the WiFi access point only. UE-B5 and UE-B6 are in the overlapping area of both LTE and WiFi coverage. In our study we analyze data transmission performance of UE-B6, which is the only node that enables LTE and WiFi interface simultaneously.

Based on this structure, the following four test cases are considered with the different parameters presented in Table II:

- *Case 1*: A single WiFi link is established between UE-A and UE-B6, which is also shared by the other nine data sink nodes. The distance between UE-B6 and the base station of LTE and WiFi is set to 60 meters respectively. The initial energy of the battery of UE-B6 is set to 300 Joules. Data stream is sent via the WiFi link with the aggregate rate of 11 Mbps using TCP as the transport layer protocol. Simulation time is 150 seconds.
- *Case 2*: Apart from UE-A and UE-B6, an extra eNB node is added as a part of the single LTE link between them instead of the WiFi link used in case 1. Other settings remain the same as in case 1.
- *Case 3*: Both WiFi and LTE links are used simultaneously for multipath data transmission and MPTCP is used as the transport layer protocol instead of TCP. Other settings remain the same as in case 2.
- *Case 4*: eMTCP is deployed to complement MPTCP. Other settings remain the same as in case 3.

In all four cases, constant bit-rate (CBR) data streams are used as input in the simulation, modeling video traffic. The data packet size was 1040 bytes which is a multiple of 26 bytes (data splicing in the output stream was employed in the NS-3 implementation of MPTCP [20]).

The NS-3 implementation of MPTCP used involves modifications of the TCP socket structure definition and the corresponding application-layer and network-layer protocols. The re-defined TCP socket used in this implementation

TABLE II
DETAILS OF FOUR TEST CASES

Case	1	2	3	4
Number of nodes	2	3	3	3
Case description	data sender and receiver	2 UE nodes (sender & receiver) and 1 eNB	2 UE nodes (sender & receiver) and 1 eNB	2 UE nodes (sender & receiver) and 1 eNB
Distance base station-receiver (m)	60	60	60	60
Aggregate data transmission rate (Mbps)	11	11	11	11
Battery capacity (Joule)	300	300	300	300
Physical link data sender-receiver	WiFi	LTE	WiFi + LTE	WiFi + LTE
Transport layer protocol	TCP	TCP	MPTCP	eMTCP + MPTCP
Simulation time (s)	150	150	150	150

includes the setting of TCP receive buffer, from which data stream is taken out to the sub-flows and then sent to the application layer. In simulations the size of the TCP receive buffer is set according to the following equation from [5]:

$$S_{buffer} = 2 \times \mathrm{sum}(BW_i) \times RTT_{max} \quad (1)$$

In equation (1), S_{buffer} represents the size of the TCP receive buffer, BW_i represents the default bandwidth set for sub-flow i (in this case, $i \in \{0, 1\}$) and RTT_{max} represents the maximum round-trip time across all the sub-flows. Setting the TCP receive buffer in the simulation using this formula avoids the sub-flows from stalling when MPTCP fast retransmission scheme is triggered on any of them.

When using the bandwidth and round-trip time values for LTE and WiFi links shown in Fig.3, the TCP receive buffer size S_{buffer} calculated by the formula from equation (1) is 2.55 Mbytes.

B. *Test Scenarios*

The following two test scenarios are designed for data transmission performance assessment:

- *Scenario 1*: studies the influence of different traffic offload size on the energy efficiency.
- *Scenario 2*: studies the energy consumption, energy efficiency and delivery performance in terms of average throughput and estimated user-perceived quality when delivering video data for the four test cases.

C. *Results Analysis*

The first scenario investigated the influence of traffic balancing between LTE and WiFi paths on the energy efficiency of eMTCP. As shown in Fig.4, the energy efficiency increases when when the traffic offloaded from LTE to WiFi increases from 0% to approximately 24% of the queued data in the TCP receive buffer. When traffic offload share increases from 24% to 100% (which indicates that all the traffic is offloaded to the WiFi link), the energy efficiency drops as the data size allocated to the WiFi link exceeds its capacity, which causes throughput decrease. The observation that there is a

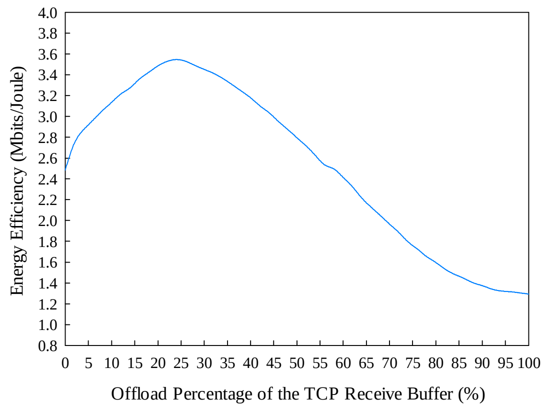

Fig.4. Change of energy efficiency according to the change of traffic offload amount

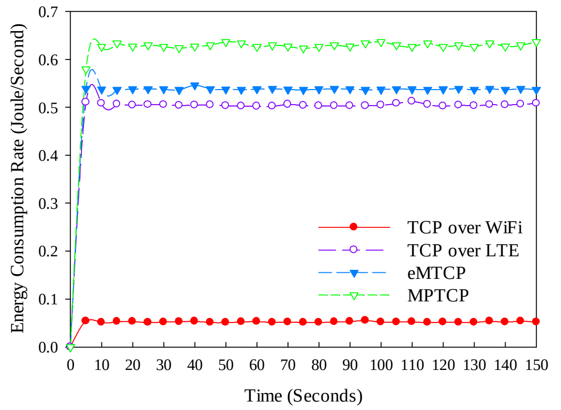

Fig.5. Energy consumption rate of the four test cases

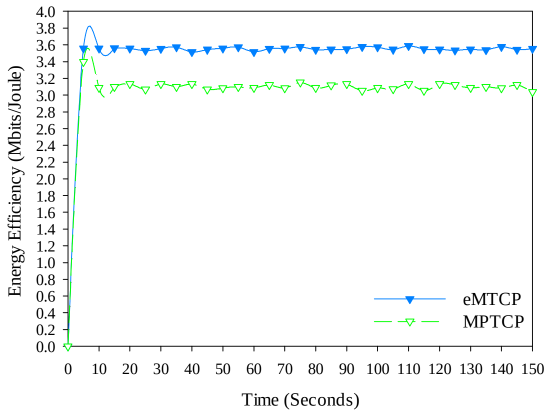

Fig.6. Energy efficiency of eMTCP and MPTCP

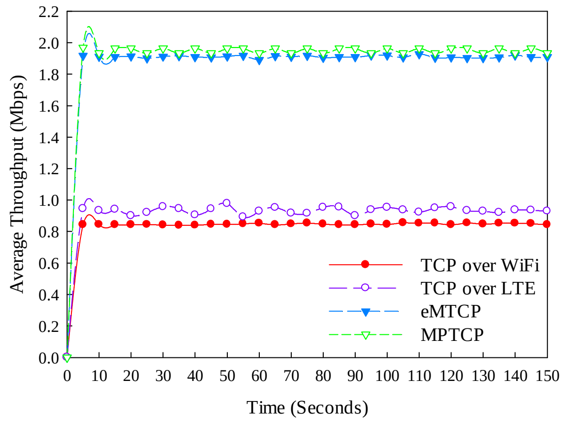

Fig.7.Average throughput of the four test cases

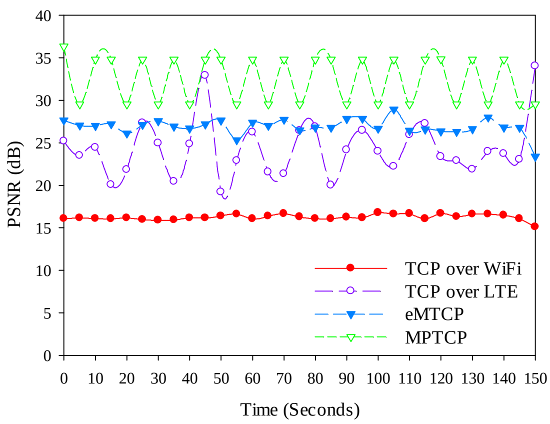

Fig.8. Estimated PSNR of the four test cases

value with the highest energy efficiency determined setting 24% as the default traffic offload percentage for the eMTCP performance evaluation in the second scenario in this paper.

In the second scenario, Fig.5 and Fig.6 show the energy consumption and energy efficiency when employing eMTCP are 14.2% and 14.1% respectively lower than when MPTCP was used. The downside of these improvements was a 2.1% decrease in the average transmission throughput, as indicated in Fig.7. Fig.7 also shows how the average transmission throughput of eMTCP is roughly 2.26 times that of TCP over WiFi and 2.05 times that of TCP over LTE. This clearly shows the data rate benefit of multipath transmissions in comparison with single-path data transfers.

The second scenario simulation-based experiments have also studied the performance of data delivery using CBR data streams. The performance is measured in terms of the Peak Signal-to-Noise Ratio (PSNR), which translates the effect of throughput and loss on user-perceived quality according to a formula from [21], presented in equation (2). Table III indicates the relationship between various PSNR values and the corresponding user-perceived quality levels as associated by the ITU T. P.800 standard [22].

$$PSNR = 20\,log_{10}\left(\frac{MAX\_Bitrate}{\sqrt{(EXP\_Thr-CRT\_Thr)^2}}\right) \qquad (2)$$

In equation (2), *MAX_Bitrate* is the average bitrate of the transmitted video stream while *EXP_Thr* and *CRT_Thr* are the expected and actual average throughput.

According to Table II, the values of *MAX_Bitrate* and *EXP_Thr* in equation (2) are 1 Mbps for case 1 and 2 and 2 Mbps for case 3 and 4 (since a two-path approach is used). PSNR values are computed and shown in Fig.8 and Table IV.

It can be noted that eMTCP's excellent energy efficiency and energy consumption results are balanced by a PSNR value

TABLE III
RELATIONSHIP BETWEEN PSNR AND USER PERCEIVED QUALITY LEVELS

PSNR (dB)	User Perceived Quality Level	Quality Level Description
>37	Excellent	Imperceptible
31-37	Good	Perceptible but not annoying
25-31	Fair	Slightly annoying
20-25	Poor	Annoying
<20	Bad	Very annoying

with 5.54 dB lower than that of MPTCP. However the value of 27.03 dB still places eMTCP's estimated user-perceived quality at "Fair" ITU T. P.800 level (see Table III). The PSNR standard deviation of eMTCP shown in Table IV is much smaller in comparison with that of MPTCP, indicating that as eMTCP results in lower PSNR fluctuations, there is important user benefit in favor of eMTCP. This is explained by the 24% traffic offload rate which leads to a better utilization of the TCP receive buffer and determines smooth throughput and PSNR. The PSNR level of eMTCP is 12.79% higher than that resulted by employing single-path TCP data transfers over LTE and 66.09% higher in comparison with that of TCP over WiFi. This clearly demonstrates the quality improvement our multipath solution has against the two single-path approaches.

The transmission performance in the four cases is also evaluated in terms of the estimated lifespan of device battery, as shown in Table IV. By using TCP over LTE there is with 8.71 times shorter battery lifespan in comparison with the duration when employing WiFi, but the signal coverage is much larger than in the WiFi case. When both WiFi and LTE interfaces are used for multipath data transmissions, it is clear that using eMTCP has a 16.51% improvement on the battery lifespan in comparison with the original MPTCP.

VI. CONCLUSIONS AND FUTURE WORK

This paper proposes eMTCP, a novel energy-aware Multipath-TCP-based content delivery mechanism which offloads data stream between LTE and WiFi interfaces of mobile devices. eMTCP is deployed at the upper transport layer and extends MPTCP in terms of energy-awareness. Simulation-based testing shows how energy saving is achieved and what performance eMTCP obtains in comparison with single-path solutions and MPTCP. In particular by employing eMTCP, up to 14.2% lower energy consumption and up to 14.1% higher energy efficiency are recorded in comparison with MPTCP. Additionally, there are increases of up to 66% and 13% in estimated user-perceived quality when using eMTCP in comparison with when single-path TCP is used over WiFi and LTE respectively. In conclusion, eMTCP best balances energy saving and increase performance of content delivery in heterogeneous wireless environments.

Future work focuses on introducing more types of wireless network interfaces such as 3G and Bluetooth into the multipath transmission performance evaluation. Also the different best data offload shares for various technologies and diverse traffic types is under investigation.

TABLE IV
PERFORMANCE EVALUATION OF FOUR TEST CASES

Case	1	2	3	4
Case Description	TCP over WiFi	TCP over LTE	eMTCP	MPTCP
Energy Consumption Rate (Joule/s)	0.052	0.505	0.539	0.628
Average Throughput (Mbps)	0.846	0.934	1.910	1.951
PSNR (dB)	16.274	23.964	27.029	32.572
PSNR Standard Deviation	0.263	2.815	0.690	2.712
Estimated Battery Life-span (Seconds)	5769.23	594.06	556.59	477.71

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